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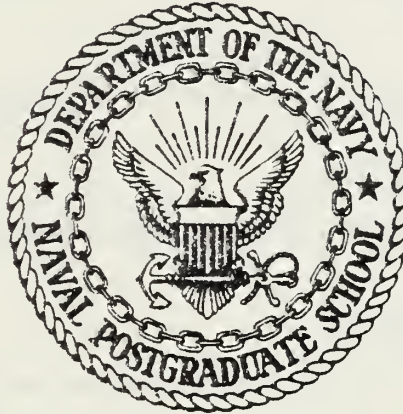
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Monterey, California



THESIS

Computer Programs for Helicopter
High Speed Flight Analysis

by

Waldo Francisco Carmona

September 1983

Thesis Advisor:

Donald M. Layton

Approved for Public Release, Distribution Unlimited

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Computer Programs for Helicopter High Speed Flight Analysis

by

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Captain, United States Army

B.A., University of Dayton, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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September 1983

ABSTRACT

This report gives the user of the HP41-CV handheld programmable calculator or the IBM 3033 computer, a blade element method for calculating the total power required in forward, straight and level high speed flight for an isolated rotor. The computer programs consist of a main program which calculates the necessary dynamic parameters of the main rotor and several subroutines which calculate power required as well as maximum forward velocity, stall onset velocity, and velocity for best endurance.

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I. INTRODUCTION

A. GENERAL

The basis for helicopter rotor analysis was developed in the early 1920's when Glauert extended propeller theory to the special case of rotating wings. Since that time, the development of the digital computer has permitted many improvements on Glauert's analysis.

In order to develop a method for predicting the total rotor power required in forward flight, it is necessary to develop a method that accurately predicts rotor dynamics. The prediction of rotor dynamics in forward flight is a complex one. Typically, a helicopter rotor blade encounters a flow environment which changes rapidly as it moves around in azimuth.

In forward flight, rotor blade sections are subjected to azimuthal variations in not only angle of attack but also Mach number. As a result, comprehensive performance analysis of a helicopter is much more involved than that of a conventional aircraft.

Recent helicopter design trends have been in the direction of increasing the maximum forward velocity possible as well as higher blade tip speeds. Since the

speed of the helicopter is added to the speed of rotation of the advancing blade, the highest relative velocities occur at the tip of the advancing blade. When the section Mach number of the blade tip exceeds the critical Mach number of the airfoil, compressibility effects result. These effects include a large increase in profile drag and change in pitching moments, therefore creating additional power requirements.

In all current helicopters there is a tendency for the retreating blade to stall. Just as the stall of an airplane wing limits the low speed performance of an airplane, the stall of a rotor limits the high speed potential of a helicopter. The relative velocity of the retreating blade decreases as forward speed increases. However, the retreating blades must produce the same amount of lift as the advancing blade. Therefore, as the relative velocity of the the retreating blade decreases with forward speed, the blade angle of attack must be increased to equalize lift throughout the the rotor disc area. As this angle increases the blade will eventually stall at some forward speed. For these reasons, stall and compressibility thus combine to limit the performance fo a helicopter at higher speeds.

For efficient design of a helicopter, the helicopter designer should have the analytical tools necessary to predict the performance of a helicopter. This report gives the user of the HP41-CV and the IBM 3033 computer a means of calculating the total power required in forward, straight and level flight.

3. OBJECTIVE

The objective was to provide an interactive computer program which can be used during the initial design stage to estimate the total power required by the main rotor of a helicopter, as well as maximum forward velocity possible, stall onset velocity, and best endurance velocity.

Additionally, the desired accuracy chosen at the beginning of this effort was to obtain angle of attack within a plus or minus one half degree, power estimates within ten per cent of the actual power required, and to obtain the needed accuracy in as short a running time as possible.

II. PROBLEM DEFINITION

A. DESCRIPTION OF PROBLEM

For a helicopter in level flight, the maximum forward speed is limited by the power available as well as stall and compressibility effects. It is therefore advantageous to develop a simple-to-use computer program that estimates blade stall and compressibility effects on helicopter performance.

B. METHOD OF SOLUTION

In forward flight, the aerodynamic environment of the rotor blade varies as the rotor blade rotates with respect to the direction of flight. The method chosen to obtain the objective accuracy ignores any variable not immediately impacting on the accuracy of the determination of angle of attack and power requirements.

The method utilized herein uses a combination of momentum and blade element theory to perform rotor performance calculations. This theory is initially used to determine the induced, profile, and parasite power required.

The solution method then utilizes a blade element analysis to predict the cyclic, collective, and inflow angles

associated with the rotor. These angles are then used in the calculation of the rotor blade's angle of attack at the azimuthal positions of 90 and 270 degrees. Compressibility and stall power are then estimated as a function of angle of attack and forward velocity.

III. DESCRIPTION OF THE PROBLEM SOLUTION

A. GENERAL

The calculation/prediction of helicopter performance is primarily a matter of determining the power required and power available over the desired flight regime. The power information may then be used to predict the operational capabilities of the aircraft.

For the ideal helicopter (no losses), in forward, straight and level flight, power required can be subdivided into five parts: induced power, P_I , required to produce rotor thrust; profile power, P_O , required to overcome the skin friction and pressure drag of the main rotor; parasite power, P_P , required to overcome the parasite drag of the helicopter; compressibility power, P_M , required to overcome the increase in profile drag when the tip Mach number exceeds the drag divergence Mach number of the airfoil; and stall power, P_S , required to account for the increase in rotor torque as a result of retreating blade stall. The HP41-CV and IBM 3033 computer programs contained herein provides a simple, quick means of evaluating the power required by an isolated rotor.

B. ASSUMPTIONS

The major task in helicopter performance analysis is the determination of rotor forces, angles, and power. The method chosen ignores any variable that does not directly impact on the desired accuracy. Therefore, in order to simplify the computational process used, the following assumptions are made:

1. Steady flow through the rotor system.
2. Small angle approximations are a valid representation of the real world phenomena.
3. All blades considered are rectangular (non-tapered) with only uniform twist possible.
4. Hinge off-set is zero (i.e., the thrust vector passes through the C.G.).
5. The stall angle on most helicopter blades can be approximated by the angle that occurs at CLMAX for a 2-D airfoil.
6. The helicopter is trimmed. This implies that the sum of all the moments about the center of gravity (C.G.) is zero, all forces are in balance, and that no lateral flapping is present.

7. At stall onset, the value of section drag coefficient jumps approximately 0.08.

8. The rotor rotates counterclockwise.

C. NOMENCLATURE

"Standard" nomenclature is used. Appendix A contains an alphabetical list defining all the symbols and mnemonics used in the development of this report. Appendix B contains an alphabetical list of all HP41-CV displays used in the HP41-CV program.

D. INITIALIZATION

It is assumed that the initial design of the helicopter has been completed and that the helicopters weight as well as the chord, radius, tip velocity, twist, zero-lift drag coefficient, and number of blades of the rotor are known. Finally, it is assumed that an initial estimation of equivalent flat plate area is available, and that the forward velocity of the helicopter is known.

E. ROTOR DYNAMICS

There are four rotor parameters which will help expedite later calculations. The first of these is the rotor advance ratio, μ ; μ is the ratio of the helicopter's forward

velocity to the rotational velocity. The advance ratio can be represented as

$$(1) \quad \mu = \frac{V_F \cos \alpha}{V_T} \quad (\text{dimensionless})$$

Applying small angle approximations the advance ratio becomes

$$(2) \quad \mu = \frac{V_F}{V_T}$$

where,

$$V_T = (\Omega R)$$

The second dimensionless ratio that needs to be calculated is the inflow ratio, λ . The inflow ratio is the ratio of the net velocity up through the rotor system to the tip speed. For the near hover case, $\mu < 0.1$, the $\tan \alpha = 0$ and the inflow ratio can be approximated by

$$(3) \quad \lambda = - \sqrt{CT/2}$$

In forward flight, the calculation of λ requires the determination of the angle of attack of the rotor disc. Letting the angle of attack between the disc plane and the

incoming free-stream velocity be α_3 , and assuming angles to be small, the inflow velocity can be calculated using

$$(3a) \quad \lambda = \frac{-C_T}{2\sqrt{\lambda^2 + \mu^2}} + \mu \tan \alpha_3$$

where

$$\alpha_3 = -\tan(D_P/L) = -\tan(D_P/W)$$

$$D_P = (P_P * 550) / V_F$$

The last dimensionless parameter that needs to be calculated is solidity. Solidity is the fraction of the rotor disc area that is composed of blades. For a blade of constant chord (i.e., non-tapered) solidity can be expressed as

$$(4) \quad \sigma = (b * C) / (\pi * R)$$

Finally, the tip loss factor, B_{TL} , must be considered. The tip loss factor is used to account for the loss of lift that a rotor blade experiences due to flow from the rotor's lower surface to its upper surface. The tip loss factor of a rotor can be approximated by

$$(5) \quad B_{TL} = 1.0 - \sqrt{2 * C_T} / b$$

F. VELOCITY CALCULATIONS

There are four velocities that are of interest. The first of these is the downwash velocity, w . Assuming steady flow through the rotor, the downwash velocity can be approximated by

$$(6) \quad w = \frac{W}{2 \rho A_D V_F} \quad (\text{ft/s})$$

NOTE: This equation is not valid for small values of forward velocity.

The second velocity that needs to be calculated is the stall onset velocity, V_S . The stall onset velocity is the velocity at which the retreating blade tip first exceeds the static stall angle. The forward speed at which stall onset is first noted can be approximated by the velocity for best range, VBR. This is due to the marked increase in profile power required at speeds higher than velocity for best range. A typical set of power curves for a helicopter are shown in Figure 3.1.

The forward velocity for minimum P/V (i.e., best range velocity) is easily found graphically on the power required curve as the point where a straight line through the origin

POWER REQUIRED VS VELOCITY

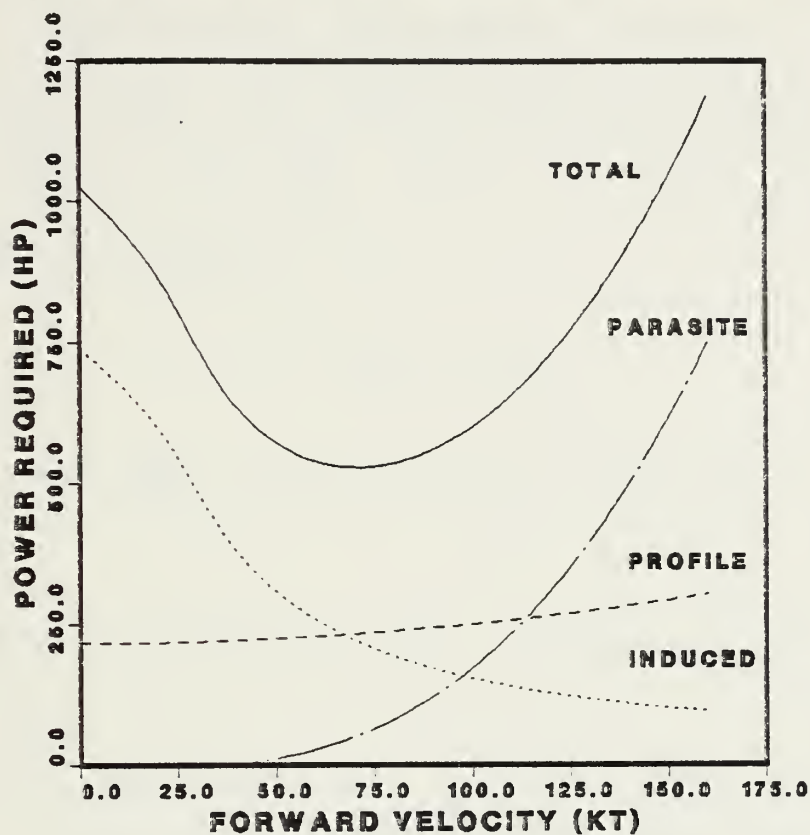


Figure 3.1. Typical Helicopter Power Curves

is tangent to the curve (see Figure 3.2). Since the power curves are not initially known, an analytical expression needs to be developed which will estimate the velocity for best range. The following is the derivation of one such expression.

As shown below, if the parasite power required is set equal to the profile power required and the equality is then solved for an equation in which forward velocity is the variable, the result is a cubic equation in which the largest root defines the point where the profile power and parasite power are equal.

$$P_P = P_O$$

$$1/2 \rho f V_F^3 = 1/8 \sigma C_{D0} \rho A_D (1 + 4.25 \mu^2)$$

$$(7) \quad V_F^3 - (4.25 / 4f) C_{D0} A_D V_T V_F^2 - (\sigma / 4f) C_{D0} A_D V_T^3 = 0$$

Next, the largest root of equation 7 needs to be determined. This can be simply done using the cubic root equation. Letting

$$p = - (4.25 \sigma / 4f) C_{D0} A_D V_T$$

$$r = - (\sigma / 4f) C_{D0} A_D V_T^3$$

Equation 7 can now be written as

$$(7a) \quad V_F^3 - p V_F^2 - r = 0$$

Substituting

$$(X - p/3)$$

for V_F in equation 7a yields an equation of the form

$$(7b) \quad X^3 + aX + b = 0$$

where,

$$a = -1/3 p^2$$

$$b = 1/27 (2p^2 + 27z)$$

The largest root of equation 7b is then given by

$$(8) \quad V = A + B$$

where,

$$A = \left[\frac{-b}{2} + \sqrt{\frac{b^2}{4} + \frac{a^3}{27}} \right]^{1/3}$$

$$B = \left[\frac{-b}{2} - \sqrt{\frac{b^2}{4} + \frac{a^3}{27}} \right]^{1/3}$$

Equation 8 can now be used as the initial approximation for stall onset velocity.

The third velocity which is of interest is the helicopter's maximum forward velocity, V_{MAX} . As shown in

Figure 3.2, the maximum forward velocity is given by the intersection of the power required and power available curves for a given gross weight and altitude [Ref. 1].

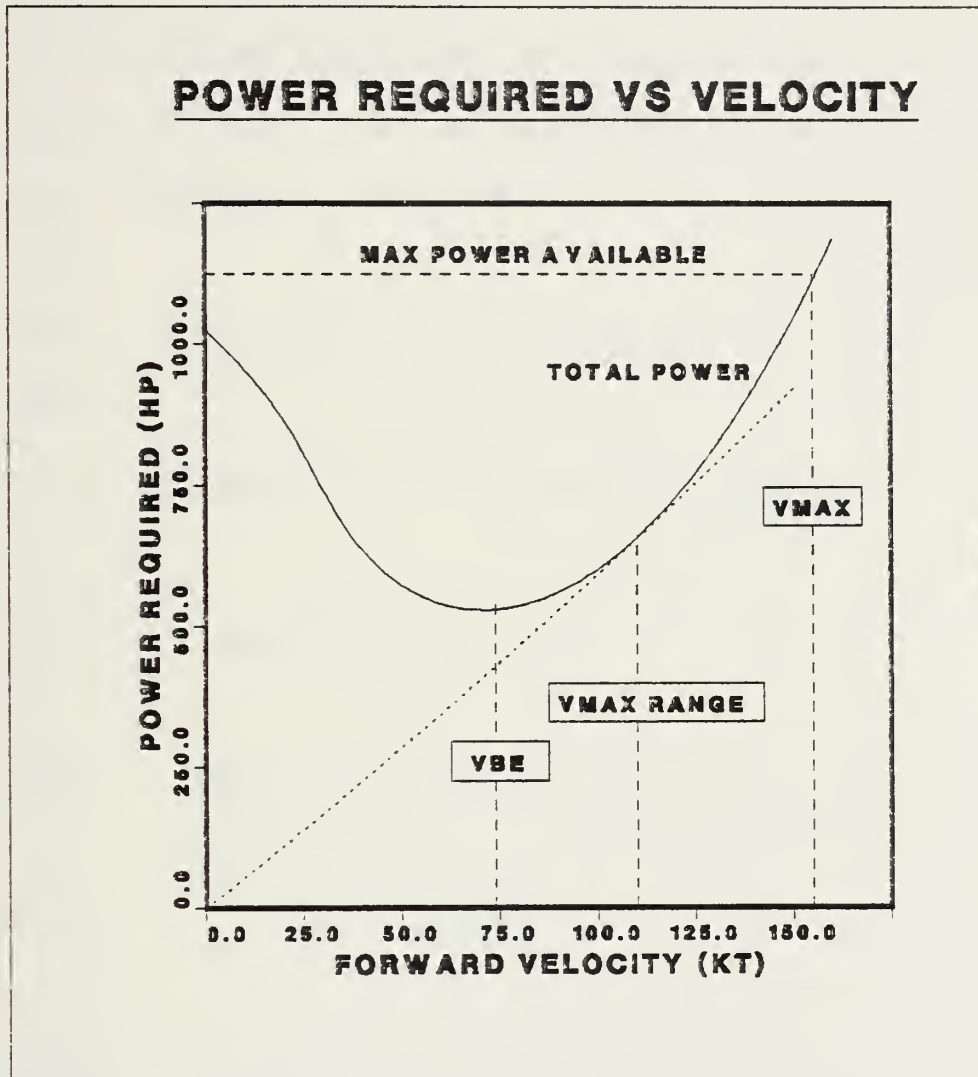


Figure 3.2. VMAX,VBE, and VS from Power Available Curves.

Therefore, whenever $V_F > V_{MAX}$, there is insufficient power available to sustain level flight.

The power-limited maximum speed may be estimated by

$$(9) \quad v_{MAX} = \frac{2}{\sigma f} (P_{AVAIL} - P_I - P_0)^{1/3} \quad (\text{ft/sec})$$

Equation 9 can be simplified by assuming that the power required at maximum speed is about the same as that required at hover. Therefore, assuming

$$(10) \quad (P_{AVAIL} - P_I - P_0) = (P_{HOVER} - P_0)$$

and that

$$(P_{AVAIL} - P_0) = (P_{IHOVER}) = \sqrt{\frac{W}{2\rho A_D}}$$

equation 9 can then be written as

$$(10a) \quad v_{MAX} = v_I * (4/f/A_D)^{1/3} \quad (\text{ft/s})$$

where,

$$(10b) \quad v_I = \sqrt{\frac{W}{2\rho A_D}}$$

The last velocity that needs to be calculated is the best endurance velocity, VBE. In the normal operating range the total helicopter power can be represented by

$$(11) \quad P_T = P_I + P_0 + P_P$$

Assuming that the variation of profile power with forward velocity is negligible, the velocity for best endurance (also the best rate of climb velocity) can be found. If equation is differentiated with respect to forward velocity, V_F , and is set equal to zero, it can be seen that

$$(11a) \quad P_I = 3 P_P$$

or

$$(11b) \quad \frac{W^2}{2 \rho A_D V_{BE}} = \frac{3 \rho \epsilon V_F^2}{2}$$

Solving equation for the best endurance velocity, V_{BE} , results in

$$(11c) \quad V_{BE} = \left[\frac{W}{\rho A_D} \left[\frac{A_D}{3\epsilon} \right]^{\frac{1}{2}} \right]^{\frac{1}{2}} \quad (\text{ft/s})$$

G. INITIAL POWER CALCULATIONS

As forward velocity increases, the induced power decreases, the profile power increases slightly, and the parasite power increases until it becomes the dominant loss at high speeds [Ref. 2]. For forward, straight and level flight, the induced power can be calculated by

$$(12) \quad P = W \left[-\frac{V_F^2}{2V_I^2} + \sqrt{\left(\frac{V_F^2}{2V_I^2}\right)^2 + 1} \right]^{\frac{1}{2}} V_I / 550 \quad (\text{hp})$$

If tip losses are taken into effect (equation 5), the induced power now becomes

$$(12a) \quad P_I = (1/B_{TL}) * P_I \quad (\text{TL})$$

Since the induced power required in ground effect is less than that required out of ground effect, equation 12 should be written as

$$(12b) \quad P_I = (1/B_{TL}) * (GE) * P_I \quad (\text{TL+GE})$$

where,

$$GE = (-0.1276 * (h/D)^4 + 0.708 * (h/D)^3 - 1.4569 * (h/D)^2 + 1.3432 * (h/D) + 0.5147)$$

The profile power required is given by

$$(13) \quad P_O = \frac{\sigma C_d \rho A_D V_I^3 (1 + 4.25 \mu^2)}{4400} \quad (\text{hp})$$

Finally, parasite power given by

$$(14) \quad P_P = \frac{\rho F V_F^3}{1100} \quad (\text{hp})$$

H. ANGLE OF ATTACK

The determination of angle of attack at the azimuthal positions of 90 and 270 degrees are important in the determination of compressibility and stall effects. It is because of this effect that the dynamics of the blade motion are important in analyzing helicopter performance.

The angle of attack of the rotor is a function of radius, r , and azimuthal position, ψ . Figure 3.3 illustrates the sign convention used in determining blade angle of attack. The angle of attack of a rotor can thus be estimated by,

$$(15) \quad \alpha(r, \psi) = \frac{\Theta - V_F \beta \cos \alpha + w - V \alpha_3}{\Omega R + V_F \sin \psi} \quad (\text{rads})$$

where,

$$(15a) \quad \Theta = \Theta_0 + \Theta_T + \Theta_1 \cos \psi + \Theta_2 \sin \psi + K_B \beta$$

$$(15b) \quad \beta = \beta_0 - a_1 \cos \psi - b_1 \sin \psi$$

ANGLE OF ATTACK

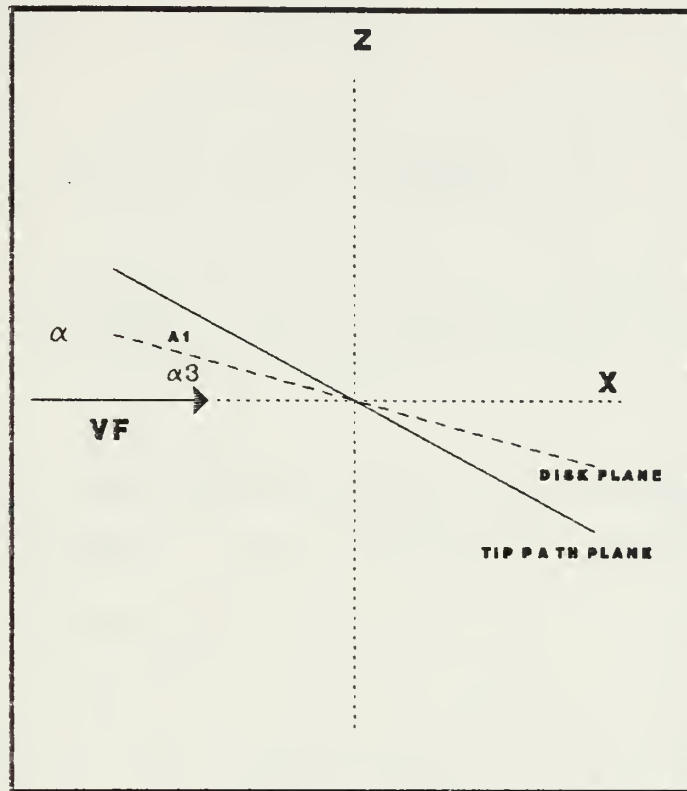


Figure 3.3. Rotor Angles in Longitudinal Plane.

To determine angle of attack, it is then necessary to determine the longitudinal collective and cyclic angles θ_0 and θ_2 . This can be accomplished by expressing the coefficient of thrust as

$$(16) \quad C_T = \frac{a\sigma}{2} \lambda T1 + (\theta_0 + K_B \beta) T2 + \theta_T T3 + (\theta_2 - K_B b1) T4$$

where,

$$T1 = .5 (B_{TL}^2 + .5 \mu^2) \quad T3 = .25 B_{TL}^2 (B_{TL}^2 + \mu^2)$$

$$T2 = (.5 B_{TL}^3 + .5 \mu^2 B_{TL}) \quad T4 = .5 \mu (B_{TL}^2 + .25 \mu^2)$$

Additionally, the longitudinal flapping coefficient $a1$, needs to be determined. The longitudinal flapping coefficient can be written as

$$(17) \quad a1 = \lambda A11 + (\theta_0 + K_B \beta) A12 + \theta_T A13 + (\theta_2 - K_B b1) A14$$

where,

$$D1 = (B_{TL}^2 - .5 \mu^2)$$

$$A11 = \frac{.25 (.5 B_{TL}^2 - \mu^3 / 8)}{B_{TL}^2 D1}$$

$$A13 = \frac{2 \mu B_{TL}^2}{D1}$$

$$A12 = \frac{8 \mu B_{TL}}{3 D1}$$

$$A14 = \frac{B_{TL}^2 + 1.5 \mu^2}{D1}$$

Assuming that there is no lateral flapping and that the effect is zero (i.e., $K_B = 0.0$), equations 16 and 17 become

$$(18) \quad \frac{2}{a} C_T = \lambda T_1 + \theta_0 T_2 + \theta_T T_3 + \theta_2 T_4$$

$$(19) \quad a_1 = \lambda A_{11} + \theta_0 A_{12} + \theta_T A_{13} + \theta_2 A_{14}$$

NOTE: Since the analysis is only looking at the azimuthal positions of 90 and 270 degrees, it can be seen from equation 15b that the contribution of the longitudinal flapping coefficient, a_1 , will always be zero at these positions.

Equations 18 and 19 now represent a set of simultaneous equations in which the only unknowns are the collective and cyclic angles and can thus be determined. Knowing the values of the cyclic and collective angles, the blade tip angle of attack at the 90 and 270 degree positions can be estimated by

$$(20) \quad \alpha_{90} = \theta_0 + \theta_T + \theta_2 + \frac{\lambda}{1+\mu}$$

$$(21) \quad \alpha_{270} = \theta_0 - \theta_2 + \theta_T + \frac{\lambda}{1+\mu}$$

NOTE: The angle of attack, α , is defined positively if the disk plane is nose up, see Figure 3.2.

I. STALL POWER

In the helicopter stall normally starts at the tip of the retreating blade, since the highest angles of attack are usually at the blade tip. As the forward speed increases, the stalled area of the rotor blade spreads inboard.

At the higher values of μ , the effects of stall on power required are great and therefore need to be estimated. Assuming a jump of 0.08 in the value of C_{do} at stall onset, that the rotor area within which the blade stall exists is a segment of minimum dimensionless radius X_S and that the stall area is symmetric about $\psi = 270$ degrees, Castles and New found that the effects of tip stall on power required at the higher values of μ are large and can be approximated for high speed flight by

$$(22) \quad C_{PS} = \frac{\sigma}{24 \pi} (1 - \mu)^2 (1 - X_S) \sqrt{1 - X_S^2}$$

where X_S is the nondimensional radius outboard of which the retreating blade is stalled [Ref. 3]. The dimensionless radius, X_S , can be estimated by equating the section angle of attack, at $\psi = 270$ degrees, to $AMAX$ [Ref. 4]. Setting equation 15 at $\psi = 270$ degrees equal to $AMAX$ results in the quadratic listed below.

$$(23) \quad (X - \mu) = \Theta_0(X - \mu) + \Theta_T X^2 - \Theta_T X \mu - \Theta_2(X - \mu) + \lambda + X \approx 1$$

Applying the quadratic formula to equation 23 yields the roots

$$(23a) \quad X_S = \frac{-B_S + \sqrt{B_S^2 - 4\Theta_T C_S}}{2\Theta_T}$$

$$(23b) \quad X_0 = \frac{-B_S - \sqrt{B_S^2 - 4\Theta_T C_S}}{2\Theta_T}$$

where,

$$(23c) \quad \Gamma = \alpha_{MAX} - \Theta_0 + \Theta_2$$

$$(23b) \quad C_S = \mu\Gamma + \lambda$$

$$(23e) \quad B = -\mu\Theta_T - \Gamma$$

Equation 22 is satisfactory for most cases. It is possible however, for the blade section angle of attack to be higher inboard than at the tip creating a situation which is usually referred to as inboard stalling [Ref. 5].

For the special case of inboard stalling, see Figure 3.4, the incremental stall power coefficient defined by equation 22 is too large and needs to be corrected.

INBOARD STALLING

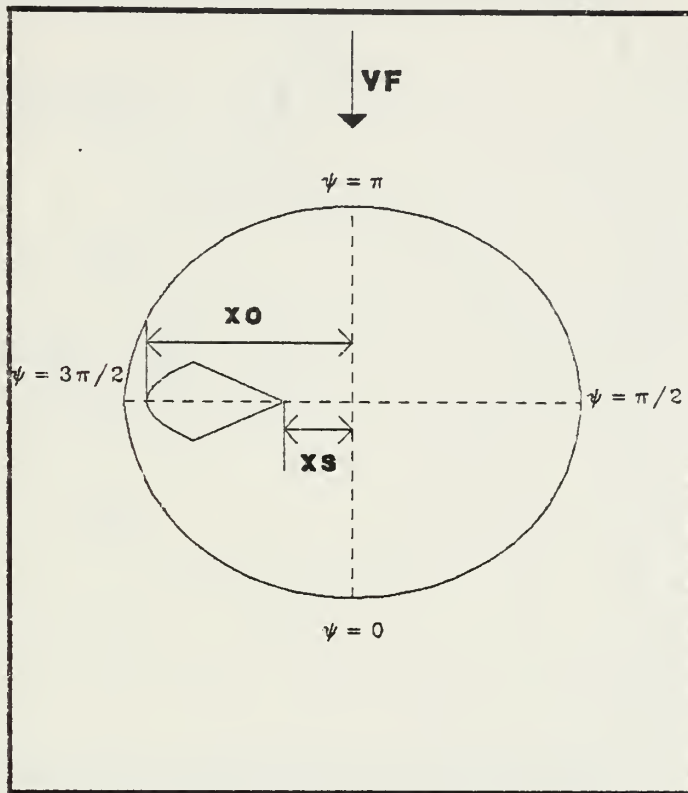


Figure 3.4. Inboard Stall Pattern.

Assuming the stalled region is diamond shaped as shown in Figure 3.5 and that the stalled area is symmetric about $\psi = 3\pi/2$, it can be seen that as x_0 approaches x_s , the correction to the incremental stall power coefficient, C_{PS} , must vanish.

STALL REGIONS

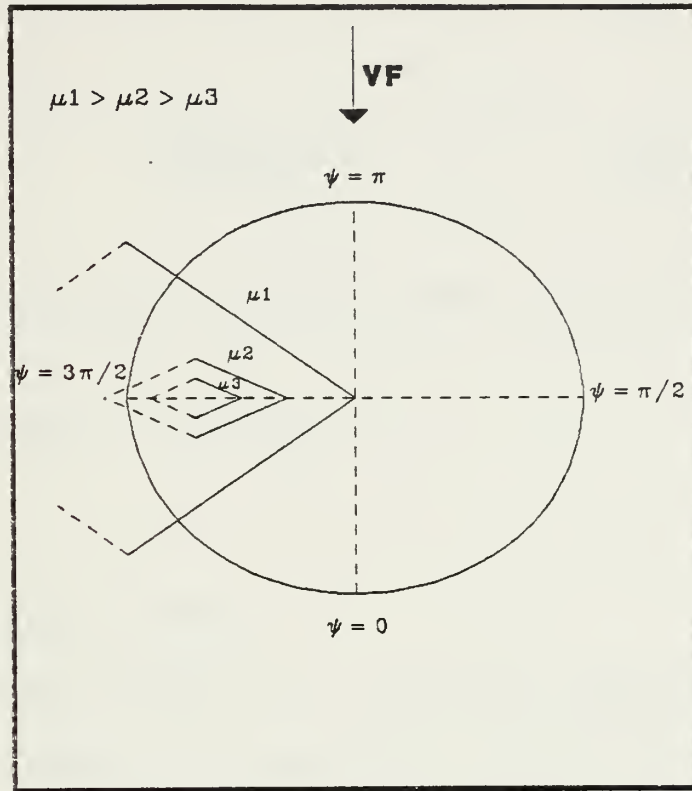


Figure 3.5. Approximated Stall Area.

Similarly, as the average of X_0 and X_S approaches unity, the value of C_{PS} goes to the value defined by equation 22.

Therefore, in order to correct for the possibility of inboard stalling, the correction factor, k_S , is defined such that

$$(24) \quad k_S = 1.0 \quad \text{for} \quad \frac{-B_S}{2\theta_T} > 1.0$$

$$(25) \quad k = \frac{B_S / 2\theta_T + X_S}{1 - X_S} \quad \text{for} \quad \frac{-B_S}{2\theta_2} < 1.0$$

The corrected equation for stall power required thus becomes

$$(26) \quad C'_{PS} = k_S * C_{PS}$$

J. COMPRESSIBILITY POWER

The individual effects of stall and compressibility on rotor profile power are substantial at high advance ratios. When both effects are present the losses due to each source are difficult to distinguish. Therefore, as a helicopter's forward velocity and tip speed increase, the need for a simple estimate of how the compressibility of the air influences the rotor performance is necessary.

In forward flight, the Mach number of the advancing blade is given by

$$(27) \quad M = M_{TIP} (x + \mu \sin \psi)$$

where,

$$(27a) \quad M_{TIP} = \frac{\Omega R}{a_{SV}} = \frac{v_T}{a_{SV}}$$

$$(27b) \quad x = r/R = \text{nondimensional radius}$$

Since the highest Mach number occurs at the tip of the advancing blade at $\psi = 90$ degrees, equation 27 can be written as

$$(28) \quad M_{90} = M_{TIP} (1 + \mu)$$

Reference 3.5 showed that the critical Mach number for drag divergence can be estimated by

$$(29) \quad M_{CRIT} = M_{CR0} - m1 * a * \alpha_{90}$$

Gessow and Crim, in their investigation of compressibility found that the compressibility effect on rotor performance was a rapid increase in the profile power when the tip Mach number exceeded the critical Mach number for drag divergence [Ref. 6]. The increase in profile power coefficient due to Mach effects can be estimated by

$$(30) \quad C_{PC} = 0.01 \Delta M_D + 0.1 (\Delta M_D)^3$$

where,

$$(31) \quad \Delta M_D = M_{90} - M_{CRIT} - 0.06$$

IV. CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to provide an easy to use, inter-active computer program which could be used during the initial design phase to estimate the total power required by the main rotor of a helicopter. The computer programs contained herein provide results which are well within the objective accuracies (see Figures C.1, C.2, C.3) and provide acceptable results as a first cut estimate of compressibility and stall power requirements.

In the development of the computational model, many simplifying assumptions were made to ease the amount of computation required. The assumption which most impacts on the accuracy of the program is that of steady flow through the rotor.

The flow environment encountered by the rotor changes rapidly due to the rate of change of blade angle of attack. Additionally, rotor operation at high advance ratios also produces considerable radial flow along the blade span. The steady flow assumption ignores the time-variant aspect of rotor aerodynamics. The dynamic nature of the rotor, especially when operating at or near the stall regime, requires the application of unsteady aerodynamics, and a

close examination of how the pitching moments generated by the retreating blade stalling affects controlability [Ref. 7]. It is therefore recommended that additional investigations consider how the unsteady aerodynamics, and pitching moments generated, influence the performance of the helicopter.

APPENDIX A
NOMENCLATURE

<u>Term</u>	<u>Mnemonic</u>	<u>Definition</u>	<u>Units</u>
a	a	Slope of airfoil section lift curve.	rad
A	AD	Rotor disc area.	ft
α_3	Alpha3	Disk plane angle of attack.	rad
α_{MAX}	AMAX	The steady flow stall angle of the airfoil (given by $a * CL_{MAX}$).	rad
α_{90}	A90	Angle of attack of the advancing blade at $\psi = 90$ degrees.	rad
α_{270}	A270	Angle of attack of the retreating blade at $\psi = 270$ degrees.	rad
a1	a1	Longitudinal flapping	rad
A11	A11	Term in definition of THETA2.	dimensionless
A12	A12	Term in definition of THETA2.	dimensionless

A13	A13	Term in definition of THETA2.	dimensionless
A14	A14	Term in definition of THETA2.	dimensionless
b	b	Number of blades on the main rotor.	dimensionless
β_0	BETA0	Main rotor coning angle.	rad
B_S	BS	Term in definition of X_S .	dimensionless
B_{TL}	BTl	Tip loss factor.	dimensionless
C	C	Mean chord of main rotor blade.	ft
C_{dc}	CD0	Main rotor coefficient of drag at zero lift.	dimensionless
CL_{MAX}	CLMAX	Maximum coefficient of lift (2-D).	dimensionless
C_{PC}	CPC	Correction to power coefficient due to compressibility effects.	dimensionless
C_{PS}	CPS	Correction to power coefficient due to stall.	dimensionless
C_S	CS	Term in definition of X_S .	dimensionless

C_T	CT	Coefficient of thrust of the main rotor.	dimensionless
D_p	D	Rotor disc diameter.	ft
D	DP	Parasite drag of the helicopter.	lb
ΔM_D	DMD	Term in the definition of compressibility power.	dimensionless
δ_3	DEL3	Rate of change of blade pitch with respect to blade flapping.	dimensionless
f	FPA	Equivalent flat plate area of the helicopter in forward flight.	ft
Γ	GAMMA	Term in definition of B and C .	dimensionless
G. E.	GE	Ground effect ratio.	dimensionless
h	H	Height of main rotor above the ground.	ft
hp	HP	Horsepower.	hp
K	KB	effect.	dimensionless

λ	LAMB	Ratio of the net velocity up through the rotor system to the tip speed.	dimensionless
M	MACH	Mach number of rotor blade.	dimensionless
M_{CRIT}	MCRIT	Critical Mach number of advancing blade at $\psi = 90$ degrees.	dimensionless
M_T	MT	Tip Mach number of rotor blade.	dimensionless
M_{CRTO}	MCRT0	Critical Mach number for $C_l = 0.0$.	dimensionless
μ	MU	Main rotor advance ratio.	dimensionless
m1	M1	Constant in definition of critical Mach number (m1 = 0.113).	ft-lb
Ω	OMEGA	Rotational velocity.	rad/s
P_C	PM	Power required due to compressibility effects.	hp
P_I	PI	Induced power.	hp

P_O	PO	Profile power.	hp
P_P	PP	Parasite Power.	hp
P_S	PS	Power required due to stall effects.	hp
R	R	Main rotor radius.	ft
ρ	RHO	Air density.	slug/ft
σ	SD	Main rotor solidity.	dimensionless
Θ	THETA	Ratio of ambient temp- erature to standard sea level temperature.	dimensionless
Θ_0	THETA0	Main rotor collective pitch.	rad
		Main rotor lateral pitch.	rad
Θ_2	THETA2	Main rotor longitudinal cyclic pitch.	rad
T1	T1	Term in definition of THETA0.	dimensionless
T2	T2	Term in definition of THETA0.	dimensionless
T3	T3	Term in definition of THETA0.	dimensionless
T4	T4	Term in definition of	dimensionless

THETA0.

V_I	VI	Induced velocity.	ft/s
V_F	VF	Aircraft forward speed.	ft/s
V	VKT	Aircraft forward speed.	kt
VMAX	VMAX	Maximum forward velocity possible.	kt
V_S	VS	Stall onset velocity (velocity at which A270 equal AMAX)	kt
V_T	VT	Rotor tip speed.	ft/s
a_{SV}	SVEL	Speed of sound.	ft/s
w	DW	Rotor downwash velocity.	ft/s
W	W	Aircraft gross weight.	lb
X_S	XS	Radius outboard of which the main rotor is stalled.	dimensionless
X_0	X0	Radius inboard of which rotor blade stall may be present due to inflow ratio and blade twist.	dimensionless

APPENDIX B

HP 41-CV PROGRAM DOCUMENTATION

A. GENERAL

The HP 41-CV program uses 45 program storage registers. Prior to program initialization, the handheld calculator should be sized to 46.

The computer program consists of a main program which calculates the necessary dynamic parameters of the main rotor and several subroutines which calculate power required as well as the maximum forward velocity, stall onset velocity, and best endurance velocity.

The documentation for the HP 41-CV program is divided into the following sections:

1. PURPOSE

This section describes the intended purpose of the program or subroutine.

2. ASSUMPTIONS

This section lists any assumptions made which are applicable to the program or subroutine.

2. EQUATIONS

This section lists the equations utilized within the main program or subroutine. The primary references for

the equations used are Aerodynamics and V/STOL Flight, Reference 3.1, Helicopter Theory, Reference 3.2, and Aircraft Performance, Reference 3.3.

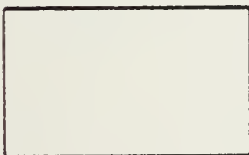
4. FLOWCHART

Both the handheld computer and the IBM 3033 normally execute instructions in a program in a sequential manner unless it is instructed to do otherwise. This section will graphically represent the step by step method used to solve the problem as well as the flow of control between the various parts of the program. In a flowchart, different types of operations are indicated by different shaped boxes as illustrated below:



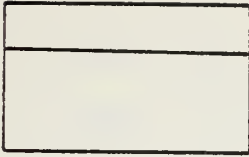
Oval

For start or stop.



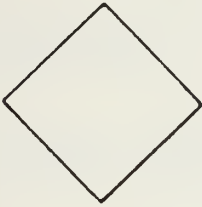
Rectangle

For a calculation or process other than a decision.



Modified
Rectangle

For the execution of
a subroutine.



Diamond

For a decision.



Parallelogram

For input or output.



Small Circle

For an on page
connection when a
flowchart continues
on the same page, or
when it is difficult
to connect two boxes.



Pentagon

For connection when
a flowchart continues
to another page.

5. PROGRAMS AND SUBROUTINES

This section lists all the programs or subroutines which must be present in the HP 41-CV prior to program execution.

6. PROGRAM LISTING

This section contains the HP 41-CV listing of the program or subroutine.

B. QUICK REFERENCE TABLES

The tables in this section will be useful to the user of the HP 41-CV handheld calculator as a source of quick reference. Table 1 is an alphabetical listing of all calculator displays with an explanation of their respective meaning. Table 2 lists all storage registers used and describes how they are utilized.

1. HP41-CV Displays

TABLE I

<u>DISPLAY</u>	<u>DEFINITION</u>	<u>UNITS</u>
a = ?	Slope of airfoil lift curve.	rad
b = ?	Number of main rotor blades.	N/A
c = ?	Chord length of main rotor.	ft
DA = ?	Density altitude.	ft
Cdc = ?	Main rotor coefficient of drag at zero lift.	N/A
FPA = ?	Equivalent horizontal flat plate area of the helicopter.	ft
h = ?	Height of the main rotor above the ground.	ft
MCRO=?	Critical Mach number for the coefficient of lift equal to zero.	N/A
R = ?	Main rotor radius.	ft
TWIST = ?	Geometric twist of the rotor.	rad
VF(KT) = ?	Forward velocity.	Kt
VT = ?	Rotor tip speed.	ft/s
W = ?	Aircraft gross weight.	lbs
COLL =	Main rotor collective pitch.	rad

CYCLIC =	Main rotor cyclic pitch.	rad
PI =	Induced power required compensated for tip losses and ground effect.	hp
PM =	Power required due to compressibility effects.	hp
PO =	Profile power required.	hp
PS =	Power required due to the retreating blade stalling.	hp
VBE =	Maximum endurance velocity.	Kt
VF > VMAX	The forward velocity that has been input is larger than the one calculated by subroutine VMAX.	N/A
VMAX =	Maximum forward velocity.	Kt
VS =	Initial estimate for finding onset velocity.	Kt
XS =	Radius outboard of which the main rotor is stalled.	N/A
XO =	Radius inboard of which rotor blade stall may be present.	N/A
α_{90D} =	Angle of attack of the advancing blade at = 90 degrees.	deg
α_{270} =	Angle of attack of the retreating	deg

blade at $\psi = 270$ degrees.

2. HP41-CV Register Utilization

TABLE II

STORAGE

<u>REGISTER</u>	<u>STORED QUANTITY/USE</u>
00	Ground effect ratio (GE).
01	Maximum forward velocity (VMAX).
02	Stall onset velocity (VS).
05	Rotor radius (R).
06	Number of blades (b).
07	Zero-lift drag coefficient (Cdo).
09	Rotor height above the ground (h).
10	Aircraft gross weight (W).
11	Air density (RHO).
12	Lift curve slope (a).
13	Rotor tip velocity (VT).
14	Coefficient of thrust (CT).
15	Tip-loss factor (BTL).
16	Main rotor induced power (PI).
17	Rotor height to rotor diameter ratio (h/d).
18	Compressibility power (PC).

19	Solidity (SD).
20	Induced velocity (VI).
21	Main rotor profile power (PO).
22	Advance ratio (MU).
23	Stall power (PS).
24	Advance ratio squared (MU^2).
25	Forward velocity (VF).
26	Equivalent horizontal flat plate area (FPA).
27	Maximum 2-D lift coefficient (CLMAX).
28	Main rotor parasite power (PP).
29	Main rotor geometric twist (TWIST).
41	Angle of attack at 270 degrees (A270).
42	Angle of attack at 90 degrees (A90).
43	Sonic velocity (SVEL).
44	Critical Mach number for coefficient of lift equal to zero (MCR0).
45	Density altitude.
OTHERS	Scratch pad calculations.

C. PROGRAM DOCUMENTATION

This section contains the necessary documentation for the HP 41-CV computer program. The main program as well as all of the subroutines used in the solution of the problem are outlined in this section.

1. Main Program

(a) PURPOSE

This program calculates the dynamic parameters of the main rotor which are necessary for calculating the total main rotor power required in forward, high speed straight and level flight. It additionally controls the execution sequence of the various subroutines which are used to calculate main rotor power required, in terms of horsepower, as well as maximum forward velocity, stall onset velocity and velocity for best endurance in knots.

(b) ASSUMPTIONS

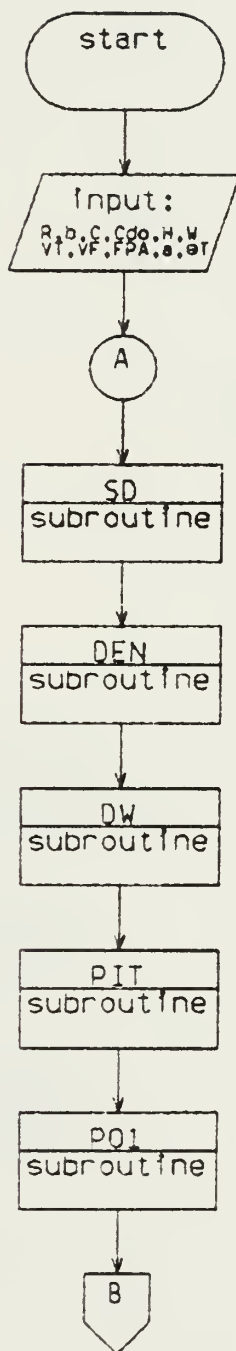
- (1) All angles are small.
- (2) Steady flow through the rotor.
- (3) All rotor blades are rectangular (non-tapered) with only uniform twist being possible.
- (4) Only the first harmonic of flapping is necessary for calculating power required.
- (4) The effective dimensionless radius can be approximated by the tip-loss factor.
- (6) The thrust vector passes through the C.G..
- (7) The static stall angle for blades on most helicopters can be approximated by the angle at which C_{LMAX} occurs for the 2-D airfoil.

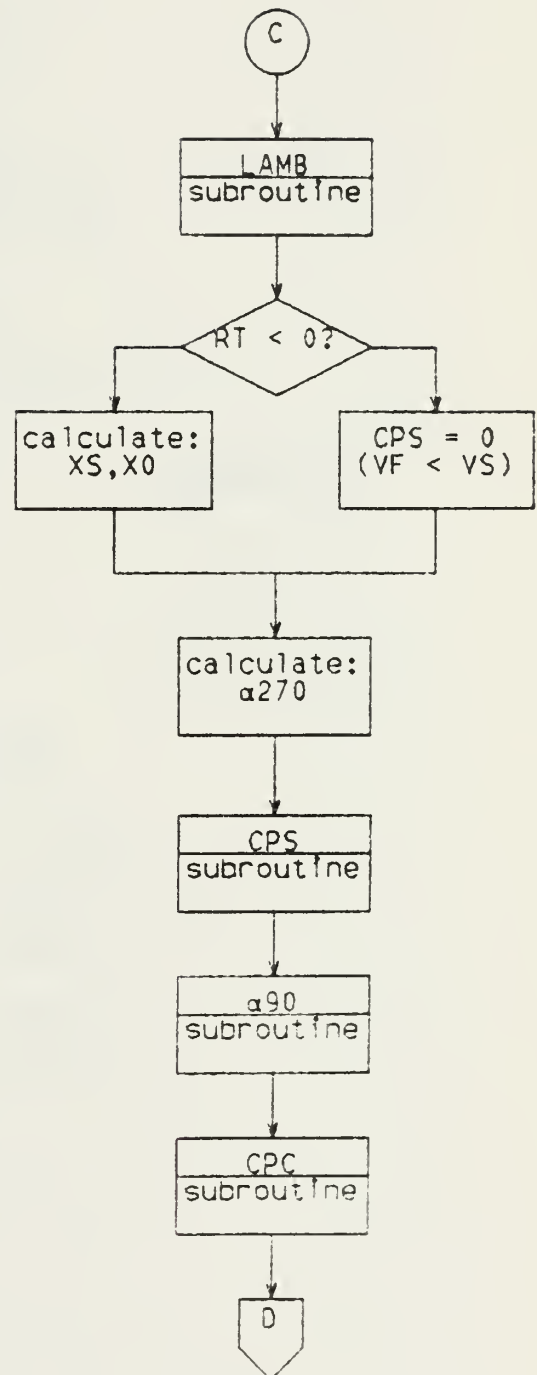
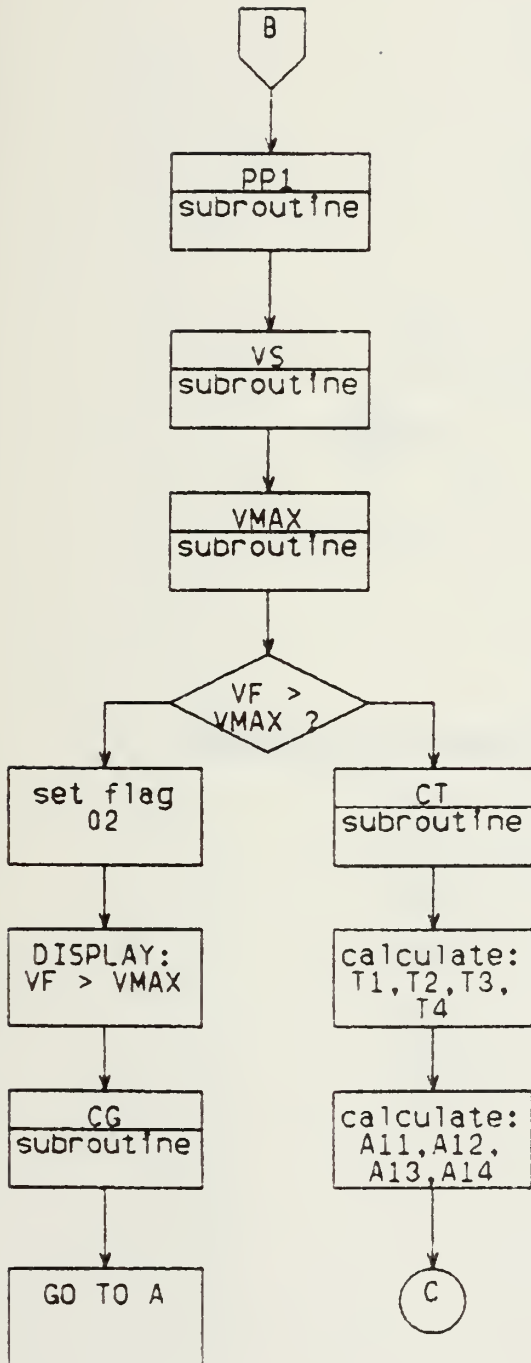
- (8) The $\delta 3$ effect, or the result of cocking the flapping axis of the blade so that its pitch varies as the blade flaps is zero (i.e., no lateral flapping is present).

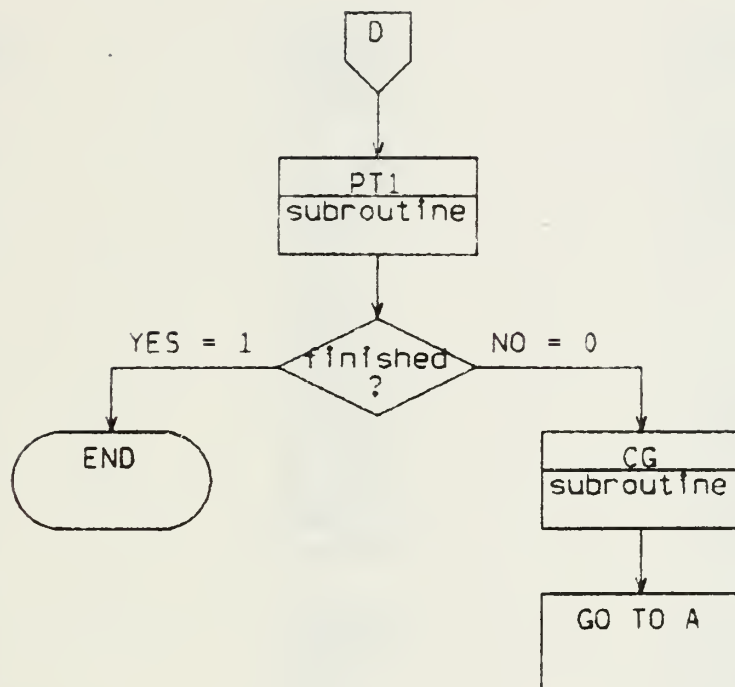
(c) EQUATIONS

$$\begin{aligned} \mu &= V_F/V_T \\ V_F \text{ (ft/s)} &= V * 1.68894 \\ T1 &= .5 (B_{TL}^2 + .5 \mu^2) \\ T2 &= .334 B_{TL}^3 + .5 \mu^2 B_{TL} \\ T3 &= .25 B_{TL}^2 (B_{TL}^2 + \mu^2) \\ T4 &= .5 \mu (B_{TL}^2 + .25 \mu^2) \\ D1 &= (B_{TL}^2 - .5 \mu^2) \\ A11 &= 4 (.5 B_{TL}^2 - \mu^3 / 8) / D1 \\ A12 &= 8 \mu B_{TL} / 3 D1 \\ A13 &= 2 \mu B_{TL}^2 / D1 \\ A14 &= (B_{TL}^2 + 1.5 \mu^2) / D1 \\ (2CT/\sigma a) &= \lambda T1 + \theta_0 T2 + \theta_T T3 + \theta_2 T4 \\ 0 &= \lambda A11 + \theta_0 A12 + \theta_T A13 + \theta_2 A14 \\ Amax &= CLMAX/CLA \\ a270 &= \theta_0 - \theta_2 + \theta_T (\lambda / 1 + \mu) \\ \Gamma &= AMAX - \theta_0 - \theta_2 \\ C_S &= \mu \Gamma + \lambda \\ B_S &= - \mu \theta_T - \Gamma \\ X_S &= -B_S + (B_S^2 - 4 \theta_T C_S)^{.5} / 2 \theta_T \\ X_0 &= -B_S - (B_S^2 - 4 \theta_T C_S)^{.5} / 2 \theta_T \end{aligned}$$

d. FLOWCHART







e. PROGRAMS AND SUBROUTINES USED

" SD "	" CT "
" PIT "	" LAMB "
" PO1 "	" CPS "
" PP1 "	" CPC "
" VS "	" α90 "
" VMAX "	" CNG "
" DEN "	

f. PROGRAM LISTING

01*LBL "WBS"	43 "DA=?"	82 3
02 "R=?"	44 PROMPT	83 Y↑X
03 PROMPT	45 STO 45	84 3
04 STO 05		85 /
05 "b=?"	46*LBL "AGN"	86 ENTER↑
06 PROMPT	47 RCL 25	87 RCL 24
07 STO 06	48 RCL 13	88 RCL 15
08 "C=?"	49 /	89 *
09 PROMPT	50 STO 22	90 2
10 STO 04	51 X↑2	91 /
11 "Cd0=?"	52 STO 24	92 +
12 PROMPT	53 XEQ "SD"	93 STO 34
13 STO 07	54 XEQ "DEN"	94 RCL 30
14 "W=?"	55 FS? 03	95 RCL 24
15 PROMPT	56 GTO 05	96 +
16 STO 10	57 XEQ "PIT"	97 RCL 30
17 "VT=?"	58 XEQ "P01"	98 *
18 PROMPT		99 4
19 STO 13	59*LBL 05	100 /
20 "VF(KT)=?"	60 XEQ "PP1"	101 STO 35
21 PROMPT	61 ADV	102 RCL 30
22 1.68894	62 FS? 03	103 RCL 24
23 *	63 GTO 06	104 4
24 STO 25	64 XEQ "VBE"	105 /
25 "FPA=?"	65 XEQ "VMAX"	106 +
26 PROMPT	66 ADV	107 RCL 22
27 STO 26		108 *
28 "H=?"	67*LBL 06	109 2
29 PROMPT	68 XEQ "CT"	110 /
30 STO 09	69 RCL 15	111 STO 36
31 "a=?"	70 X↑2	112 RCL 22
32 PROMPT	71 STO 30	113 RCL 30
33 STO 12	72 ENTER↑	114 *
34 "CLMAX=?"	73 RCL 24	115 2
35 PROMPT	74 2	116 /
36 STO 27	75 /	117 RCL 22
37 "TWIST=?"	76 +	118 3
38 PROMPT	77 STO 31	119 Y↑X
39 STO 29	78 2	120 8
40 "MCR0=?"	79 /	121 /
41 PROMPT	80 STO 33	122 -
42 STO 44	81 RCL 15	123 4

124 *	166 RCL 12	207 -
125 RCL 30	167 /	208 /
126 ENTER↑	168 RCL 19	209 STO 32
127 RCL 24	169 /	210 FS? 03
128 2	170 STO 42	211 GTO 07
129 /	171 XEQ "LAMB"	212 R-D
130 -	172 RCL 03	213 "CYCLIC="
131 STO 32	173 RCL 33	214 ARCL X
132 RCL 30	174 *	215 AVIEW
133 *	175 CHS	216 STOP
134 /	176 RCL 42	
135 STO 37	177 +	217+LBL 07
136 RCL 22	178 RCL 29	218 RCL 31
137 RCL 15	179 RCL 35	219 ENTER↑
138 *	180 *	220 RCL 36
139 8	181 -	221 RCL 32
140 *	182 STO 31	222 *
141 3	183 RCL 03	223 -
142 /	184 CHS	224 RCL 34
143 RCL 32	185 RCL 37	225 /
144 /	186 *	226 STO 33
145 STO 38	187 RCL 29	227 FS? 03
146 RCL 22	188 RCL 39	228 GTO 08
147 2	189 *	229 R-D
148 *	190 -	230 "COLL="
149 RCL 30	191 STO 32	231 ARCL X
150 *	192 RCL 34	232 AVIEW
151 RCL 32	193 *	233 STOP
152 /	194 ENTER↑	234 ADV
153 STO 39	195 RCL 31	
154 RCL 30	196 RCL 38	235+LBL 08
155 ENTER↑	197 *	236 RCL 33
156 RCL 24	198 -	237 RCL 32
157 1.5	199 RCL 34	238 -
158 *	200 ENTER↑	239 RCL 29
159 +	201 RCL 40	240 +
160 RCL 32	202 *	241 ENTER↑
161 /	203 RCL 36	242 RCL 03
162 STO 40	204 ENTER↑	243 1
163 RCL 14	205 RCL 38	244 RCL 22
164 2	206 *	245 +
165 *		

246 /	287 X↑2	327*LBL 03
247 +	288 STO 36	328 XEQ "CPS"
248 STO 41	289 ENTER↑	329 ADV
249 FS? 03	290 RCL 35	330 CF 01
250 GTO 09	291 CHS	331 CF 02
251 R-D	292 X>Y?	332 CF 03
252 "4270="	293 SF 01	333 XEQ "CPC"
253 ARCL X	294 FS? 01	334 ADV
254 AVIEW	295 GTO 03	335 ADV
255 STOP	296 RCL 36	336 XEQ "PT1"
256 ADV	297 RCL 35	337 XEQ "CNG"
257 XEQ "490"	298 +	
258 ADV	299 SORT	338*LBL 09
259 RCL 27	300 STO 38	339 XEQ "VS"
260 RCL 12	301 RCL 31	340 END
261 /	302 CHS	
262 RCL 33	303 +	
263 -	304 RCL 29	
264 RCL 32	305 /	
265 +	306 2	
266 STO 30	307 /	
267 RCL 22	308 STO 30	
268 CHS	309 "XS="	
269 RCL 29	310 ARCL X	
270 *	311 AVIEW	
271 RCL 30	312 STOP	
272 -	313 RCL 31	
273 STO 31	314 CHS	
274 RCL 30	315 RCL 38	
275 RCL 22	316 -	
276 *	317 RCL 29	
277 RCL 03	318 /	
278 +	319 2	
279 STO 35	320 /	
280 4	321 STO 00	
281 CHS	322 "X0="	
282 *	323 ARCL X	
283 RCL 29	324 AVIEW	
284 *	325 STOP	
285 STO 35	326 ADV	
286 RCL 31		

2. Solidity

a. PURPOSE

This subroutine calculates the ratio of total blade area to the total rotor disc area.

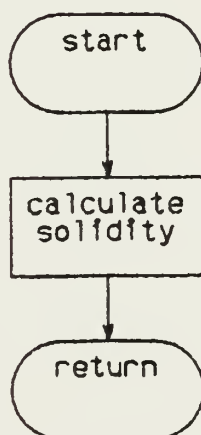
b. ASSUMPTIONS

None

c. EQUATIONS.

$$\sigma = \frac{b * c * R}{PI * R^2} = \frac{b * c}{PI * R}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01*LBL "SD"  
02 RCL 06  
03 RCL 04  
04 *  
05 RCL 05  
06 /  
07 PI  
08 /  
09 STO 19  
10 END
```


3. Downwash Velocity

a. PURPOSE

The purpose of this subroutine is to compute the induced velocity of a rotor system.

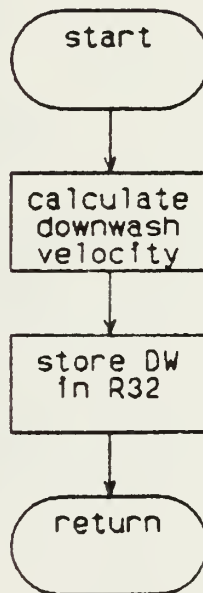
b. ASSUMPTIONS

Steady flow through the rotor system.

c. EQUATIONS

$$w = \frac{W}{2\rho A_0 V_F}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

" WBS "

f. PROGRAM LISTING

```
01+LBL "W"  
02 RCL 25  
03 X=0?  
04 GTO 05  
05 RCL 10  
06 2  
07 RCL 11  
08 *  
09 RCL 25  
10 *  
11 PI  
12 *  
13 RCL 05  
14 X↑2  
15 *  
16 /  
17 STO 64  
18 GTO 06  
  
19+LBL 05  
20 SF 03  
  
21+LBL 06  
22 END
```


4. Coefficient of Thrust

a. PURPOSE

This subroutine calculates the coefficient of thrust for a arbitrary rotor.

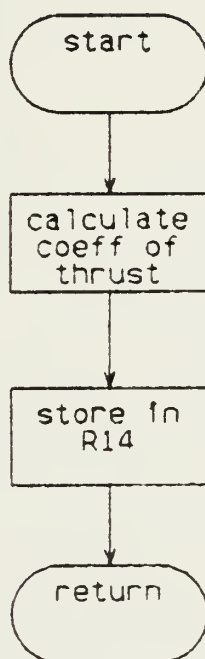
b. ASSUMPTIONS

Steady flow through the rotor system.

c. EQUATIONS

$$CT = \frac{W}{\rho A_D V_T^2}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01*LBL "CT"  
02 RCL 05  
03 X↑2  
04 PI  
05 *  
06 RCL 11  
07 *  
08 RCL 13  
09 X↑2  
10 *  
11 1/X  
12 RCL 10  
13 *  
14 STO 14  
15 END
```


5. Induced Power

(a) PURPOSE

This subroutine calculates the power required by the rotor to produce thrust at hover and forward flight. Additionally, this subroutine corrects for tip losses (losses in lift at the tips due to tip vortices) as well as ground effect.

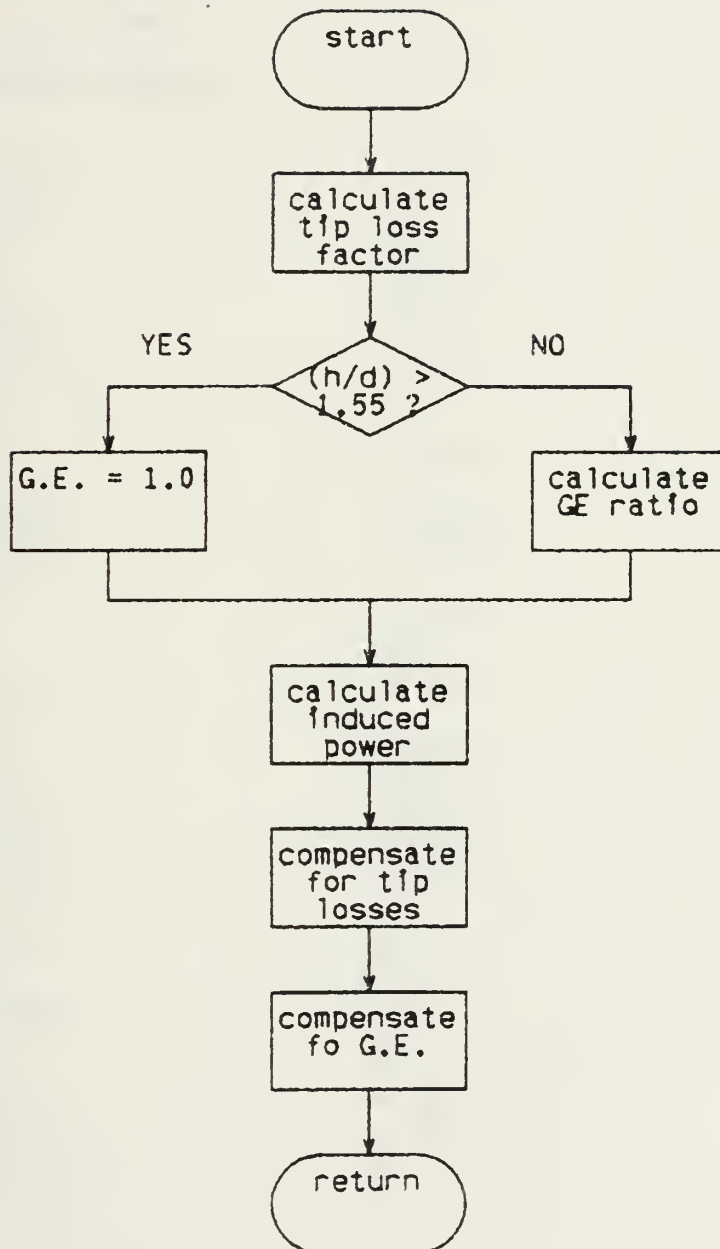
(b) ASSUMPTIONS

Steady flow through the rotor system.

(c) EQUATIONS

$$\begin{aligned}PI &= W \left[-\frac{V_F^2}{2V_I^2} + \sqrt{\left(\frac{V_F^2}{2V_I^2}\right)^2 + 1} \right]^{\frac{1}{2}} V_I \\B &= 1.0 - \sqrt{\frac{2 CT}{D}} \\GE &= -0.1276(h/D) + 0.708(h/D)^3 \\&\quad - 1.4569(h/D)^2 + 1.3432(h/D) + 0.5147 \\PIT &= (1/B) * (GE) * PI\end{aligned}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

01*LBL "PI"	33 .708	63 SQRT
02 RCL 14	34 *	64 STO 20
03 2	35 +	65 X ^{1/2}
04 *	36 RCL 17	66 1/X
05 SQRT	37 4	67 RCL 32
06 RCL 06	38 Y↑X	68 *
07 /	39 -.1276	69 2
08 CHS	40 *	70 /
09 1	41 +	71 CHS
10 +	42 .5147	72 STO 34
11 STO 15	43 +	73 X ^{1/2}
12 RCL 09	44 STO 00	74 1
13 RCL 05	45 GT0 06	75 +
14 2		76 SQRT
15 *	46*LBL 05	77 RCL 34
16 /	47 1	78 +
17 STO 17	48 STO 00	79 SQRT
18 1.5		80 RCL 10
19 X<Y	49*LBL 06	81 *
20 X>Y?	50 RCL 25	82 RCL 20
21 GT0 05	51 X ^{1/2}	83 *
22 RCL 17	52 STO 32	84 550
23 1.3432	53 RCL 10	85 /
24 *	54 2	86 RCL 15
25 RCL 17	55 /	87 *
26 X ^{1/2}	56 RCL 11	88 RCL 00
27 -1.4569	57 /	89 *
28 *	58 PI	90 STO 16
29 +	59 /	91 "PI="
30 RCL 17	60 RCL 05	92 ARCL X
31 3	61 X ^{1/2}	93 AVIEW
32 Y↑X	62 /	94 STOP
		95 END

6. Profile power

a. PURPOSE

This subroutine calculates the profile power required for forward, straight and level flight in terms of horsepower.

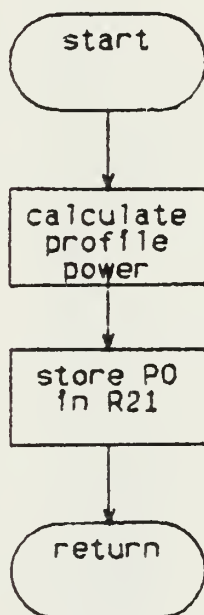
b. ASSUMPTIONS

Steady flow through the rotor system.

c. EQUATIONS.

$$P_o = \frac{\sigma C_{do} \rho A_o V_r^2 (1 + 4.25 \mu^2)}{4400} \quad (\text{hp})$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINE USED

" WBS "

f. PROGRAM LISTING

```
01*LBL "P01"  
02 RCL 19  
03 RCL 07  
04 *  
05 RCL 11  
06 *  
07 RCL 05  
08 X↑2  
09 *  
10 PI  
11 *  
12 RCL 13  
13 3  
14 Y↑X  
15 *  
16 8  
17 /  
18 STO 21  
19 RCL 24  
20 4.25  
21 *  
22 1  
23 +  
24 RCL 21  
25 *  
26 550  
27 /  
28 STO 21  
29 "P0="   
30 ARCL X  
31 RVIEW  
32 STOP  
33 END
```


7. Parasite Power

a. PURPOSE

This subroutine calculates the parasite power required in forward, straight and level flight.

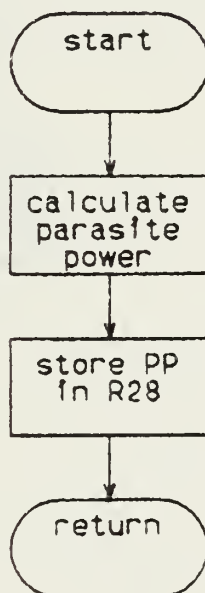
b. ASSUMPTIONS

Steady flow through the rotor system.

c. EQUATIONS.

$$PP = \frac{pfV_F^3}{1100} \quad (\text{hp})$$

d. FLOWCHART



8. PROGRAMS AND SUBROUTINES USED

" WBS "

f. PROGRAM LISTING

```
01*LBL "PP1"  
02 RCL 11  
03 RCL 26  
04 *  
05 .5  
06 *  
07 RCL 25  
08 3  
09 Y↑X  
10 *  
11 550  
12 /  
13 STO 28  
14 "PP="   
15 ARCL X  
16 RVIEW  
17 STOP  
18 END
```


8. Maximum Forward Velocity

a. Purpose

This subroutine calculates the power-limited maximum speed of the specified helicopter.

b. ASSUMPTIONS

a. The power-limited maximum velocity may be estimated by neglecting the variation of induced power and profile power with speed.

b. Power required to hover is approximately equal to power required for maximum speed.

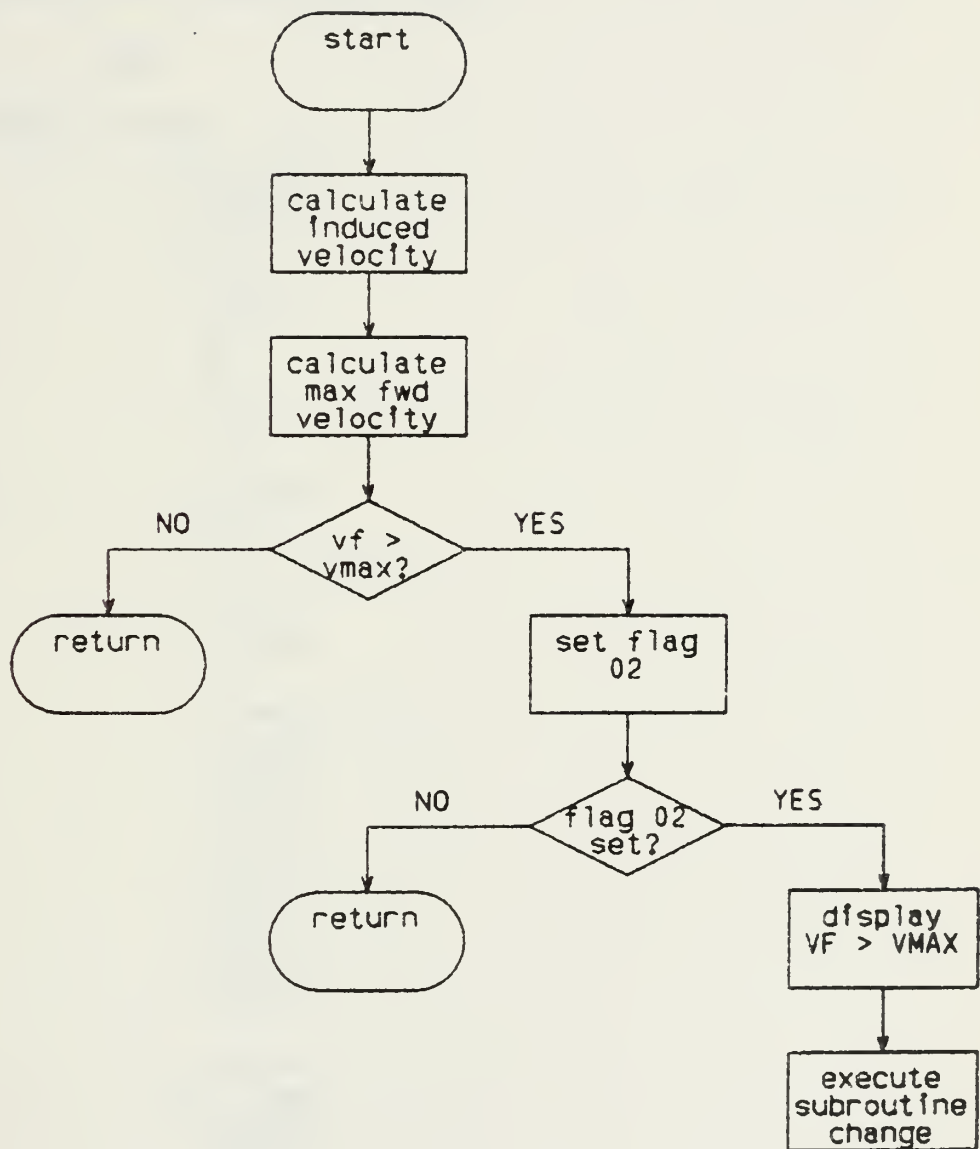
c. Steady flow through the rotor system.

c. EQUATIONS.

$$V_{MAX} = v_i \left[\frac{4}{f/A_0} \right]^{1/3}$$

$$v_i = \left[\frac{W}{2 \rho A_0} \right]^{1/2}$$

D. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01*LBL "VMAX"
02 RCL 26
03 PI
04 /
05 RCL 05
06 X↑2
07 /
08 1/X
09 4
10 *
11 .3333334
12 Y↑X
13 RCL 20
14 *
15 STO 01
16 1.6884
17 /
18 "VMAX="
19 ARCL X
20 RVIEW
21 STOP
22 RCL 01
23 RCL 25
24 X>Y?
25 GTO 12
26 X<=Y?
27 GTO 13

28*LBL 12
29 "VF > VMAX"
30 RVIEW
31 XEQ "CNC"

32*LBL 13
33 END
```


9. Best Endurance Velocity

A. PURPOSE

To calculate the value of velocity corresponding to minimum power (i.e., best endurance velocity and/or best rate of climb).

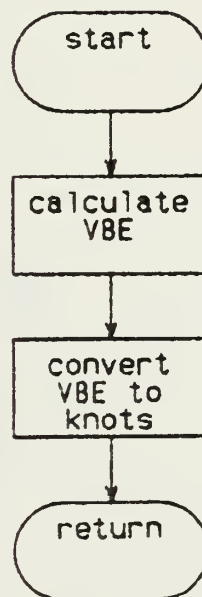
B. ASSUMPTIONS

1. Steady flow through the rotor system.
2. The variation of profile power with forward velocity is negligible.

C. EQUATIONS

$$V_{BE} = \left[\frac{W}{\rho * A} * \left(\frac{A}{3 * f} \right)^{1/2} \right]^{1/2} \quad (\text{ft/s})$$

D. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01*LBL "VBE"  
02 RCL 05  
03 X↑2  
04 PI  
05 *  
06 3  
07 /  
08 RCL 26  
09 /  
10 SQRT  
11 RCL 10  
12 *  
13 RCL 11  
14 /  
15 RCL 05  
16 X↑2  
17 /  
18 PI  
19 /  
20 SQRT  
21 1.68894  
22 /  
23 "VBEK="   
24 ARCL X  
25 RVIEW  
26 STOP  
27 END
```


10. Stall Onset Velocity

a. PURPOSE

This subroutine gives the user of the HP 41-CV an initial approximation for the velocity at which the retreating blade angle of attack is approximately equal to the is approximately equal to the static stall angle of the rotor blade.

b. ASSUMPTIONS

1. Steady flow through the rotor system.
2. Stall onset velocity is approximately equal to the velocity for best range (i.e., minimum P/V).

c. EQUATIONS.

$$p = (-4.25 \sigma C_{do} A_0 V_T) / (4f)$$

$$r = (-\sigma C_{do} A_0 V_T^3) / (4f)$$

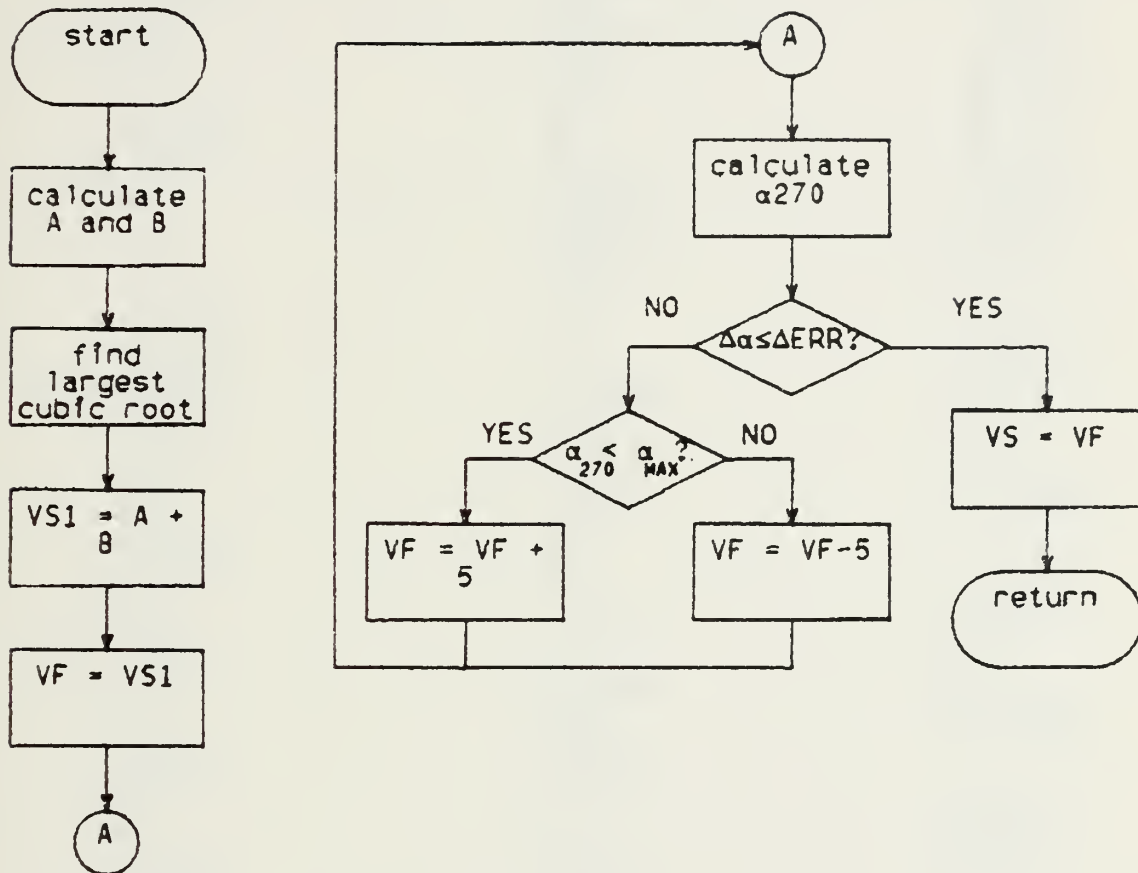
$$a = -1/3 * p^2$$

$$b = 1/27 * (2 * p^2 + 27 * r)$$

$$A = [-b/2 + (b^2/2 + a^3/27)^{1/2}]^{1/3}$$

$$B = [-b/2 - (b^2/2 + a^3/27)^{1/2}]^{1/3}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

" WBS "

f. PROGRAM LISTING

01*LBL "VS"	47 RCL 31	93 X↑2
02 FS? 03	48 X↑2	94 SORT
03 GTD 10	49 4	95 .001
04 RCL 19	50 /	96 X<>Y
05 RCL 07	51 RCL 30	97 X<=Y?
06 *	52 3	98 GTD 11
07 PI	53 Y↑X	99 RCL 31
08 *	54 27	100 RCL 41
09 RCL 05	55 /	101 X>Y?
10 X↑2	56 +	102 GTD 12
11 *	57 SORT	103 RCL 41
12 4	58 STO 33	104 RCL 31
13 /	59 RCL 31	105 X>Y?
14 RCL 26	60 CHS	106 GTD 13
15 /	61 2	
16 STO 03	62 /	107*LBL 12
17 RCL 13	63 +	108 RCL 25
18 *	64 .333334	109 5
19 4.25	65 Y↑X	110 -
20 *	66 STO 32	111 STO 25
21 CHS	67 RCL 31	112 GTD "AGN"
22 STO 01	68 CHS	
23 RCL 13	69 2	113*LBL 13
24 3	70 /	114 RCL 25
25 Y↑X	71 RCL 33	115 5
26 RCL 03	72 -	116 +
27 *	73 .333334	117 STO 25
28 CHS	74 Y↑X	118 GTD "AGN"
29 STO 02	75 STO 34	
30 27	76 RCL 32	119*LBL 11
31 *	77 +	120 CF 03
32 RCL 01	78 STO 02	121 RCL 41
33 3	79 .25	122 R-D
34 Y↑X	80 *	123 "ΔSTALL="
35 2	81 RCL 02	124 ARCL X
36 *	82 +	125 RVIEW
37 +	83 STO 25	126 STOP
38 27	84 SF 03	127 RCL 25
39 /	85 GTD "AGN"	128 1.68894
40 STO 31		129 /
41 RCL 01	86*LBL 10	130 "VS="
42 X↑2	87 RCL 27	131 ARCL X
43 -3	88 RCL 12	132 RVIEW
44 1/X	89 /	133 STOP
45 *	90 STO 31	134 END
46 STO 30	91 RCL 41	
	92 -	

11. Inflow Ratio

(a) PURPOSE

This subroutine calculates the ratio of the net velocity up through the rotor system to the tip speed.

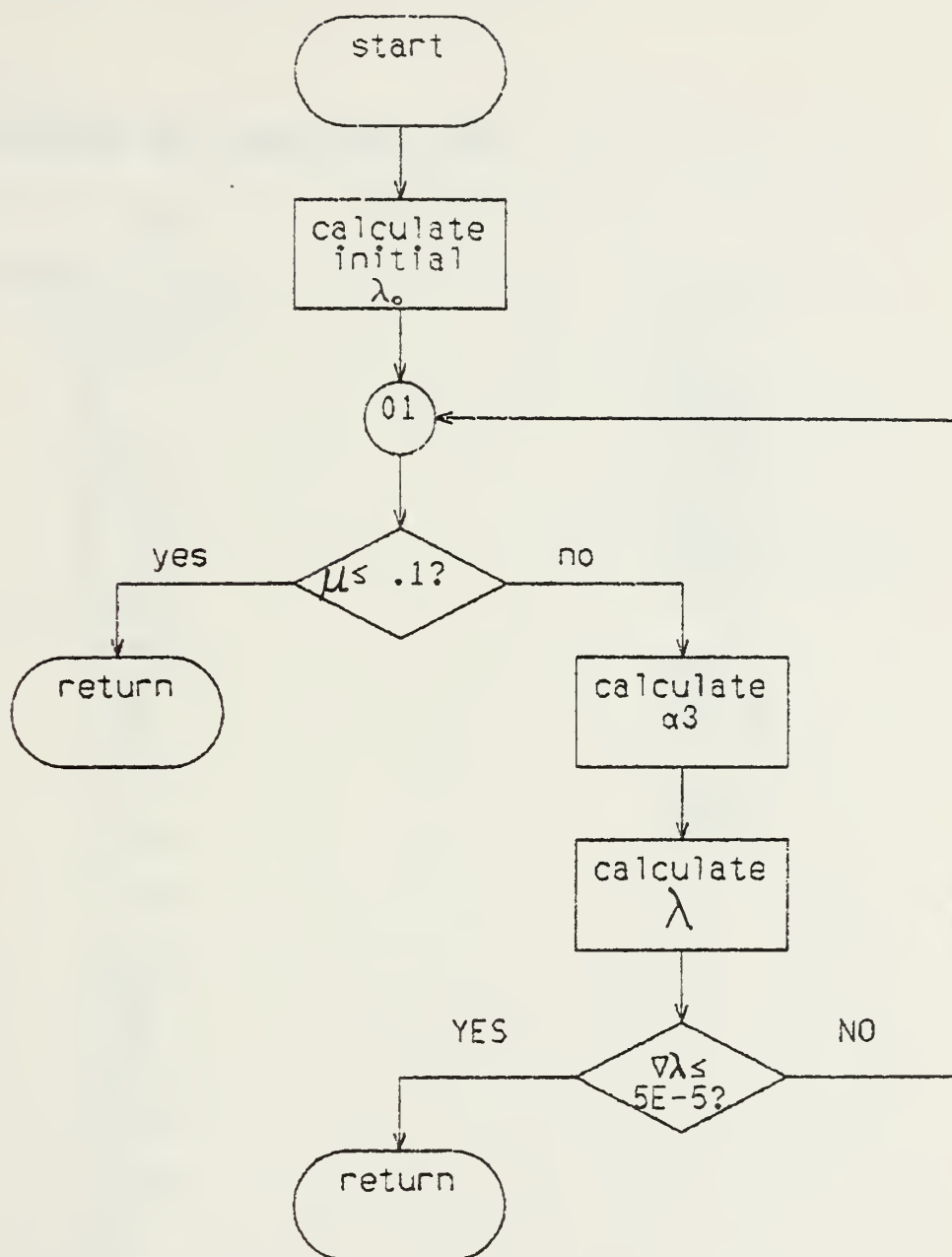
(b) ASSUMPTIONS

Steady flow through the rotor system.

(c) EQUATIONS

$$\begin{aligned}\lambda &= -\sqrt{CT/2} \\ \lambda &= \frac{-CT}{2\sqrt{\lambda^2 + \mu^2}} + \mu \tan \alpha_3 \\ D_P &= (PP*550)/V_F \\ \alpha_3 &= -\tan (D_P/W)\end{aligned}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```

01+LBL "LAMB"
02 RCL 14
03 2
04 /
05 SQRT
06 CHS
07 STO 03
08 .1
09 RCL 22
10 X<=Y?
11 GTO 06
12 RCL 28
13 550
14 *
15 RCL 25
16 /
17 RCL 10
18 /
19 STO 23

20+LBL 01
21 RCL 14
22 CHS
23 RCL 03
24 X+2
25 RCL 24
26 +
27 SQRT
28 2
29 *
30 /
31 ENTER+
32 RCL 23
33 R-D
34 TAN
35 RCL 22
36 *
37 -
38 STO 08

39 RCL 03
40 -
41 X+2
42 SQRT
43 .00005
44 X>Y?
45 GTO 02
46 RCL 08
47 STO 03
48 GTO 01

49+LBL 02
50 RCL 08
51 STO 03

52+LBL 06
53 END

```


12. Angle of Attack at 90 Degrees

a. PURPOSE

This subroutine calculates the angle of attack at the azimuthal position of 90 degrees.

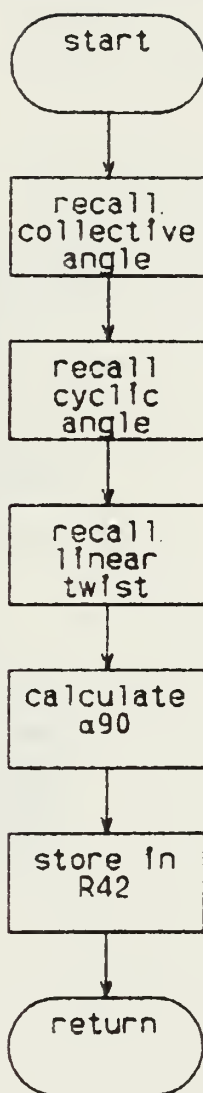
b. ASSUMPTIONS

- a. Steady flow through the rotor system.
- b. Blade oscillations are periodic in nature.
- c. Only first harmonics of flapping are necessary for calculating angle of attack.
- d. The thrust vector passes through the C.G.
- e. Only uniform twist of the rotor blade is possible.

c. EQUATIONS

$$\alpha_{90} = \theta_0 + \theta_2 + \theta_T + \frac{\lambda}{(1 + \mu)}$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

' WBS '

" α90 "

f. PROGRAM LISTING

```
01+LBL "Z90"  
02 RCL 33  
03 RCL 32  
04 +  
05 RCL 29  
06 +  
07 ENTER↑  
08 RCL 03  
09 1  
10 RCL 22  
11 +  
12 /  
13 +  
14 STO 42  
15 R-D  
16 "Z900="   
17 ARCL X  
18 RVIEW  
19 STOP  
20 END
```


13. Compressibility Power

a. PURPOSE

This subroutine calculates the power required due to compressibility on the main rotor system in forward, straight and level flight in terms of horsepower.

2. ASSUMPTIONS

a. Steady flow through the rotor system.

b. The compressibility losses can be expressed as a function of the amount by which the drag divergence Mach number is exceeded at the tip of the advancing blade.

c. EQUATIONS.

$$M_{tip} = \frac{V_t + V_{\infty}}{a_0}$$

$$\Delta M_d = M_t - M_{crit} \quad 0.06$$

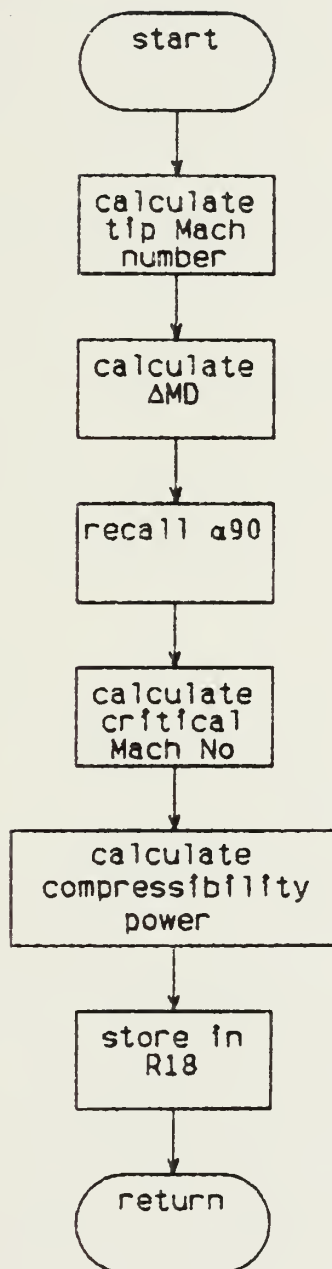
$$M_{crit} = 0.71 - 2.3 * \alpha_{90}$$

$$C_{pc} = * [0.012 * \Delta M_d + 0.1 * (\Delta M_d)^3]$$

$$P_H = \frac{C_{pc} * \rho * PI * R^2 * V_t^3}{550} \quad (HP)$$

550

d. FLOWCHART



f. PROGRAM LISTING

01*LBL "CPC"	37 RCL 19
02 RCL 13	38 *
03 RCL 25	39 STO 34
04 +	40 RCL 11
05 RCL 43	41 *
06 /	42 RCL 05
07 STO 31	43 X↑2
08 RCL 42	44 *
09 RCL 12	45 PI
10 *	46 *
11 .113	47 ENTER↑
12 *	48 RCL 13
13 CHS	49 3
14 RCL 44	50 Y↑X
15 +	51 *
16 STO 32	52 550
17 CHS	53 /
18 RCL 31	54 STO 10
19 +	55 GT0 10
20 .06	
21 -	56*LBL 09
22 STO 33	57 0
23 0	58 STO 10
24 X<Y	
25 X<=Y?	59*LBL 10
26 GT0 09	60 "PC="
27 RCL 33	61 ARCL X
28 3	62 RVIEW
29 Y↑X	63 STOP
30 .1	64 END
31 *	
32 ENTER↑	
33 RCL 33	
34 .012	
35 *	
36 +	

14. Stall Power

a. PURPOSE

This subroutine estimates the additional power required in forward, straight and level flight due to retreating blade stall. Additionally, this subroutine calculates a stall correction factor, k_s , that corrects for the special case of inboard stalling.

b. ASSUMPTIONS

- Steady flow through the rotor system.
- The section drag coefficient at stall jumps approximately 0.08 at stall onset.
- The stalled area is symmetric about the 270 degree azimuthal position.
- For all airfoils considered, the static stall angle is approximately 12.5 degrees.

c. EQUATIONS

$$\frac{-B_s}{2 * \Theta_r} \leq 1.0$$

where,

$$B_s = -U * \Theta_r - \Gamma$$

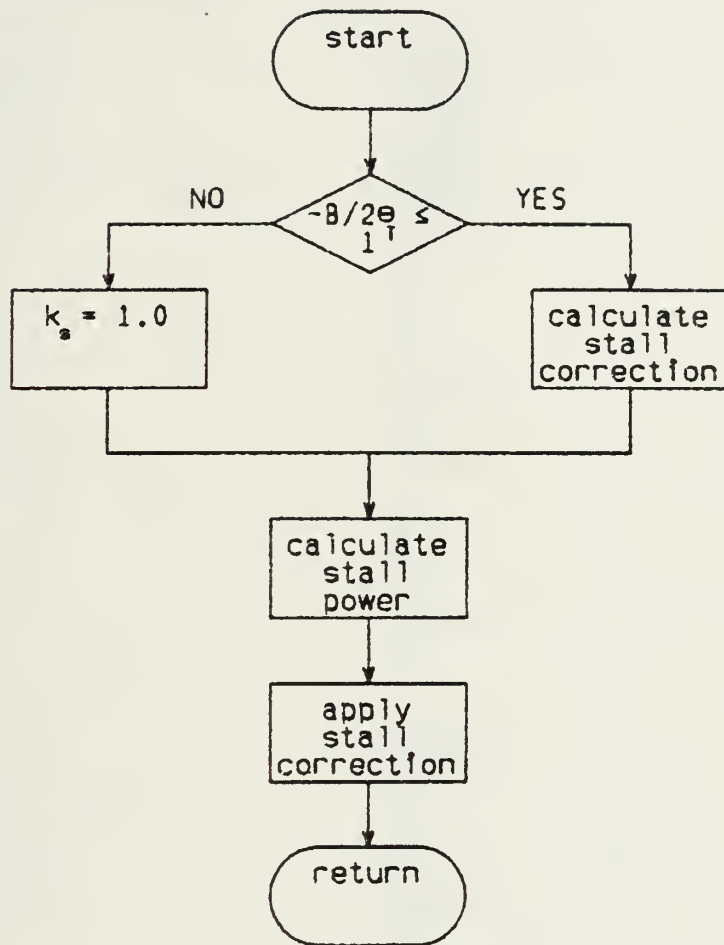
$$\Gamma = 0.218166 - \Theta_o + \Theta_2$$

$$k_s = - \left(\frac{B_s / 2 * \Theta_r + X_s}{1 - X_s} \right)$$

$$C_{ps} = \left[\frac{\sigma}{24 * \pi f} * (1 - U)^2 * (1 - X_s) * (1 - X_s^2)^{1/2} \right]$$

$$P_s = C_{ps} * \rho * PI * R^2 * V_r^3$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

" WBS "
" SD "
" CT "
" W "
" PP1 "
" LAMB "

f. PROGRAM LISTING

01*LBL "CPS"

02 FS? 01

03 GTO 06

04 RCL 30

05 RCL 08

06 +

07 2

08 /

09 1

10 X<>Y

11 X<=Y?

12 GTO 01

13 1

14 STO 23

15 GTO 02

16*LBL 01

17 RCL 31

18 2

19 /

20 RCL 29

21 /

22 RCL 30

23 +

24 CHS

25 ENTER↑

26 1

27 RCL 30

28 -

29 /

30 STO 23

31*LBL 02

32 "KS="

33 ARCL X

34 AVIEW

35 STOP

36 SF 02

37 RCL 19

38 24

39 /

40 PI

41 /

42 ENTER↑

43 1

44 RCL 22

45 -

46 X↑2

47 *

48 1

49 RCL 30

50 -

51 *

52 1

53 RCL 30

54 X↑2

55 -

56 SQRT

57 *

58 RCL 23

59 *

60 STO 23

61 RCL 13

62 3

63 Y↑X

64 RCL 23

65 *

66 PI

67 *

68 RCL 05

69 X↑2

70 *

71 RCL 11

72 *

73 550

74 /

75 STO 23

76 FS? 02

77 GTO 07

78*LBL 06

79 0

80 STO 23

81*LBL 07

82 "PS="

83 ARCL X

84 AVIEW

85 STOP

86 END

15. Total Power

a. PURPOSE

This subroutine calculates the total power required in forward, straight and level flight, to include stall and compressibility power in terms of horsepower.

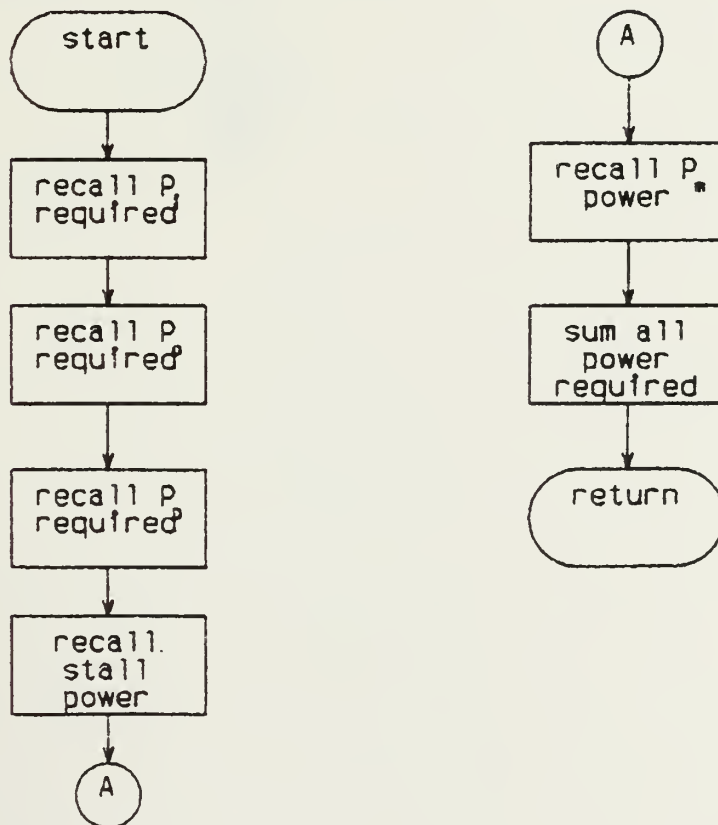
c. ASSUMPTIONS

Power losses, such as transmission and cooling, can be ignored.

c. EQUATIONS.

$$P_T = P_i + P_o + P_p + P_s + P_w$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01•LBL "PT1"  
02 RCL 28  
03 RCL 16  
04 +  
05 RCL 21  
06 +  
07 RCL 23  
08 +  
09 RCL 18  
10 +  
11 "PT="   
12 ARCL X  
13 RVIEW  
14 STOP  
15 END
```


16. Density/Sonic Velocity

a. PURPOSE

To generate values of air density and sonic velocity.

b. ASSUMPTIONS

- (1) Geopotential altitude (H), and geometric altitudes are equal below 20,000 feet (actual $\Delta H = 29$ ft).
- (2) In the troposphere the standard temperature lapse rate is -3.57°F per 1000 feet.

c. EQUATIONS

$$\theta = T/T_{SSL} = (1.0 - 6.8753 \text{ E-}06 * H)$$

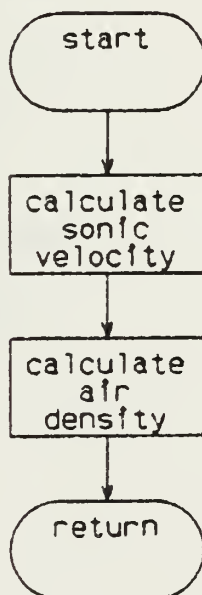
$$SVEL = SVEL_{SSL} * \text{SQRT}(\theta)$$

$$\text{RHO} = 0.0023769 * (1.0 + \text{HTH} * (-.02875 + 0.000275 * \text{HTH}))$$

where,

$$\text{HTH} = \text{DA}/1000$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

```
01*LBL "DEN"  
02 RCL 45  
03 6.875 E-06  
04 *  
05 CHS  
06 1  
07 +  
08 SQRT  
09 1116.89  
10 *  
11 STO 43  
12 RCL 45  
13 1000  
14 /  
15 STO 33  
16 .000275  
17 *  
18 -.02875  
19 +  
20 RCL 33  
21 *  
22 1  
23 +  
24 .0023769  
25 *  
26 STO 11  
27 END
```


17. Change

a. PURPOSE

This subroutine is used to expedite the changing of up to five of the input parameters whenever a design restraint is exceeded and/or at the end of the main program.

b. ASSUMPTIONS

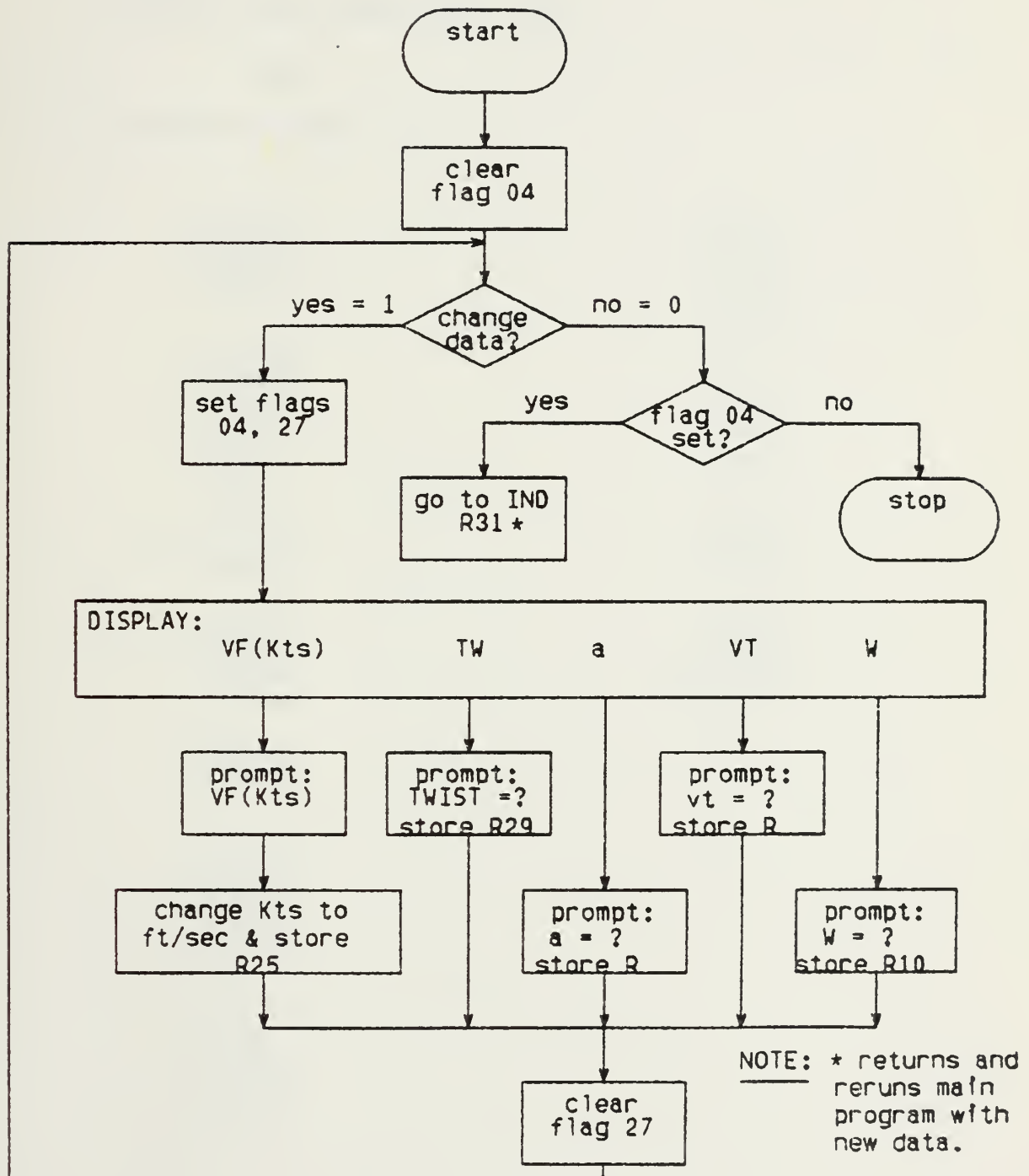
The primary parameters which will require changing are:

- a. Forward velocity, VF; (Kts)
- b. blade twist, TW; (rads)
- c. lift curve slope, a; (per rad)
- d. tip velocity, VT; (ft/sec)
- e. weight, W; (lbs)

c. EQUATIONS

$$VF \text{ (ft/sec)} = VF \text{ (Kts)} * 1.68894$$

d. FLOWCHART



e. PROGRAMS AND SUBROUTINES USED

• WBS •

f. PROGRAM LISTING

01*LBL "CNG"	31*LBL D
02 "AGN"	32 "VT=?"
03 ASTO 31	33 PROMPT
04 CF 04	34 STO 13
	35 GTO 05
05*LBL 06	
06 "CHANGE?"	36*LBL E
07 PROMPT	37 "W=?"
08 X=0?	38 PROMPT
09 GTO 07	39 STO 10
10 SF 04	
11 SF 27	40*LBL 05
12 "VF TW a VT W"	41 CF 27
13 PROMPT	42 GTO 06
14*LBL A	43*LBL 07
15 "VF<KTS>=?"	44 FS? 04
16 PROMPT	45 GTO IND 31
17 1.68894	46 END
18 *	
19 STO 25	
20 GTO 05	
21*LBL B	
22 "TWIST=?"	
23 PROMPT	
24 STO 29	
25 GTO 05	
26*LBL C	
27 "a=?"	
28 PROMPT	
29 STO 60	
30 GTO 05	

D. HP 41-CV SAMPLE OUTPUT

Depending on the value of forward velocity there are three possible types of output that the HP 41-CV computer program is capable of producing. Examples of the three possible cases are listed below.

CASE 1 : Forward velocity, VF, is less than stall onset velocity.

PI=791.751153
PO=224.584453
PP=0.000000

VS=137.762848
VBEK=76.060750
VMAX=163.448330

CYCLIC=0.000000
COLL=17.896907

Z270=4.888790

Z900=4.888790

PS=0.000000

PM=0.000000

PT=1.016.255606

CASE 2 : Forward velocity, V_F , is greater than
stall onset velocity.

PI=113.87
PO=352.43
PP=704.24

VS=137.76
VBEK=76.06
VMAX=163.45

CYCLIC=-9.39
COLL=20.76

$\angle 270 = 17.75$

$\angle 90 = -1.03$

XS=0.74
XO=1.24

KS=0.96
PS=148.90

PM=253.71

PT=1,573.16

CASE 3 : Forward velocity, V_F , is greater than
the maximum forward velocity possible.

PI=107.18
PO=368.92
PP=844.72

VS=137.76
VBEK=76.06
VMAX=163.45
 $V_F > V_{MAX}$

CYCLIC=-10.55
COLL=22.08

$\angle 270 = 19.87$

$\angle 900 = -1.23$

XS=0.73
XO=1.53

KS=1.00
PS=156.10

PM=289.23

PT=1,766.15

APPENDIX C

A. IBM 3033 PROGRAM DOCUMENTATION

This program calculates the power required to fly a helicopter in forward, straight and level high speed flight. In the sections that follow all inputs and implementation requirements are specified. The problem solving methodology used is as described in Chapter II.

B. INPUT DATA REQUIRED

In calculating the performance of a helicopter it is necessary to define a set of force conditions, environmental conditions, and physical conditions. The force conditions required are the aircraft gross weight (W) in pounds, the maximum lift coefficient (CL_{MAX}), and the coefficient of lift at zero angle of attack (C_{D0}). The environmental conditions include, forward velocity (V_{FK}) in knots, speed of sound ($SVEL$) in feet/sec, rotor height above the ground (H) in feet, and air density (RHO) in lb-ft³/sec³. For sake of user simplicity, the speed of sound and air density are generated within the program and are comparable to the values found in a standard atmosphere table. Finally, the physical conditions required are the rotor radius (R) in feet, tip velocity (VT) in ft/sec, number of blades (b), main rotor chord (C) in feet, flat plate area (FPA) in ft², geometric twist of the rotor ($TWIST$) in radians, and airfoil lift curve slope (CLA) in per radians.

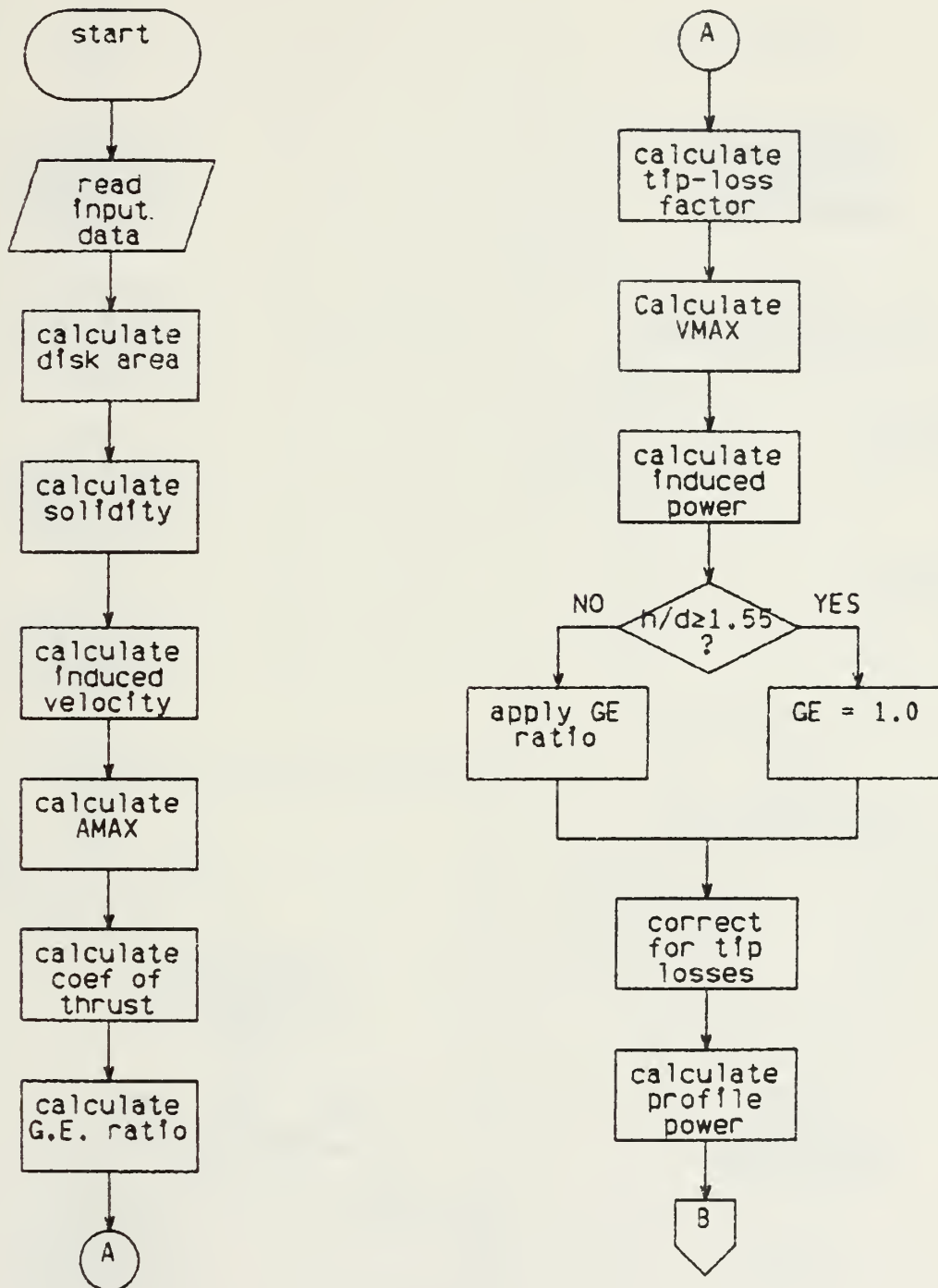
C. HELICOPTER SAMPLE DATA

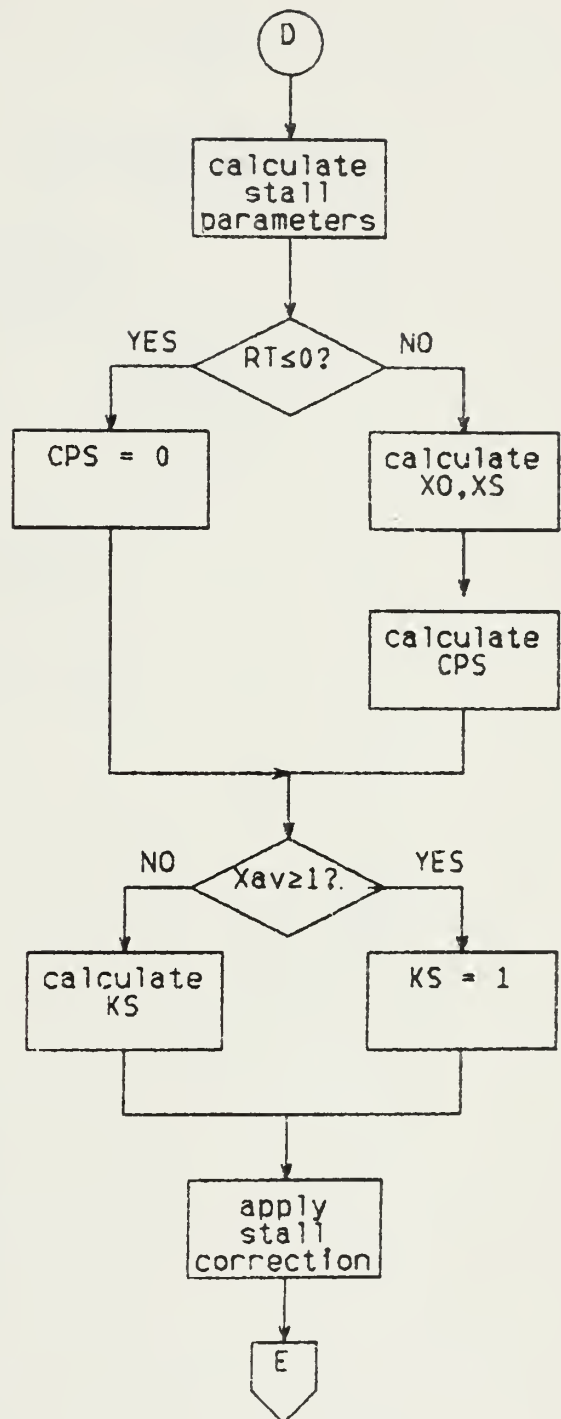
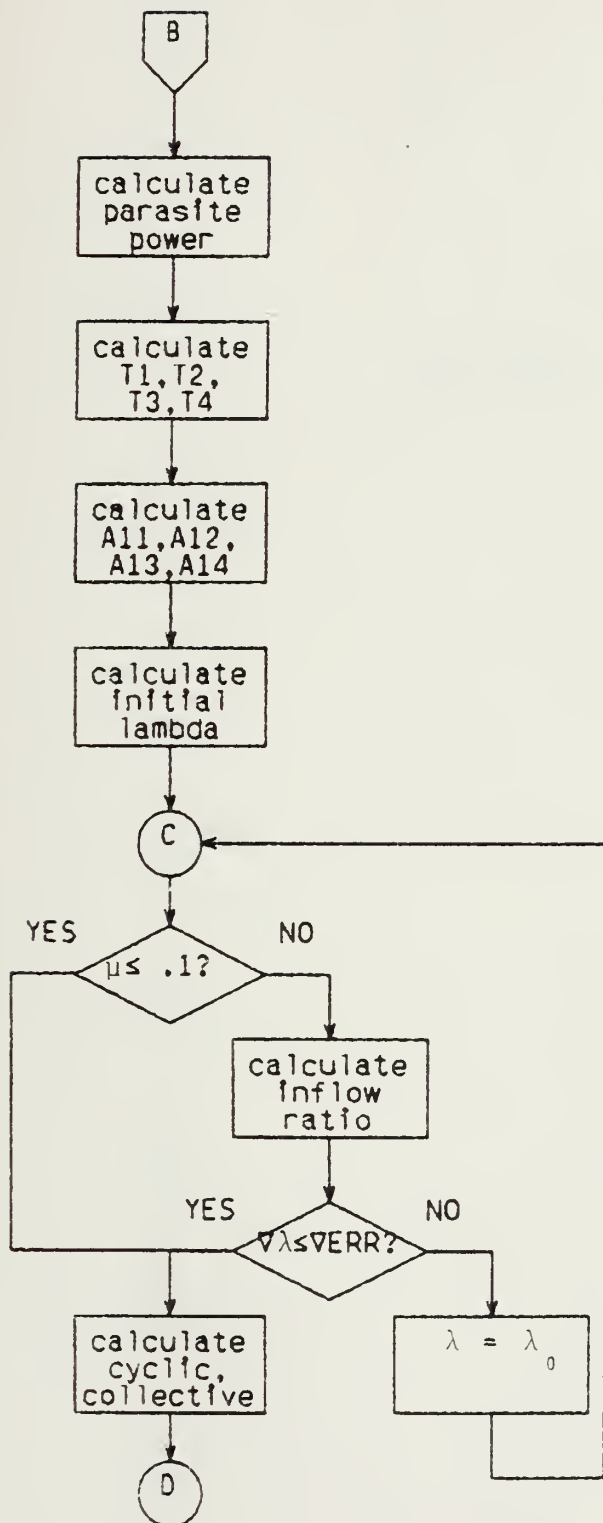
Table C.1 below illustrates the format required when inputting data.

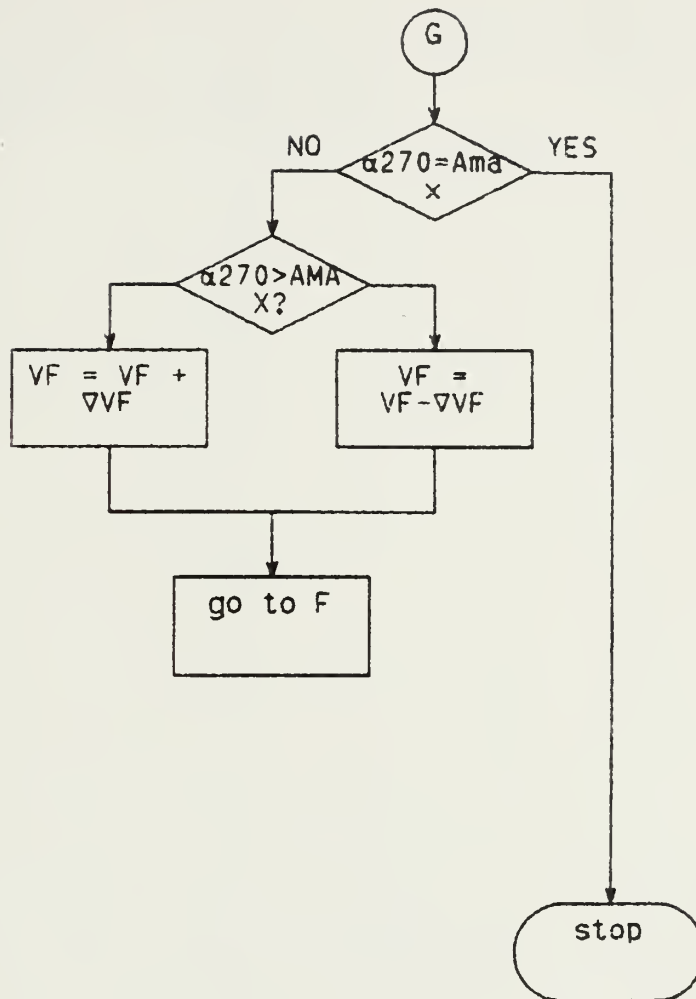
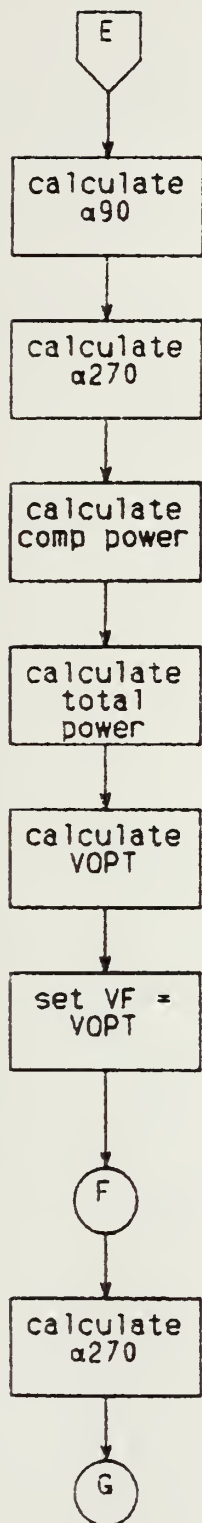
TABLE C.1 HELICOPTER SAMPLE INPUT DATA

<u>RADIUS</u>	<u>CDO</u>	<u>W</u>	<u>VT</u>	<u>FPA</u>
22.	.01075	10512.	738.0	17.
<u>TWIST</u>	<u>NO. BLADES</u>	<u>CHORD</u>	<u>INITIAL VFK</u>	<u>CLA</u>
-.1745	2.	2.25	0.0	5.73
<u>H</u>	<u>CLMAX</u>	<u>NO. ENGINES</u>	<u>TYPE AIRFOIL</u>	<u>DA</u>
1000.	1.4	2.	7.	1000.

D. IBM PROGRAM FLOWCHART







E. IBM PROGRAM LISTING

This section contains the listing of the IBM 3033 computer program developed in this report.


```

C C C C C C C
THIS PROGRAM CALCULATES THE PERFORMANCE OF A HELICOPTER
FROM HOVER TO FORWARD, STRAIGHT AND LEVEL FLIGHT, HIGH
SPEED FLIGHT.
C C C C C C C
      WRITTEN BY  CPT W. CARMONA (JUN 83)
      INTEGER NDEG,IER/O/,CENT/O/,
      REAL LAMBDA,MU,KS,K,MCRIT,MT,H,N,LERR,MCR0,LAMBD1,HTH,MCR1 TO
      DATA DERR/,COL/,NDEG/3/,LERR/,0001/,MCRITO/0.725/,DVFK/10./
      READ(5,200)R,CDC,W,VT,FPA,TWIST,B,C,VFK,CLA,H,CLMAX,N,TYPE,DA
      WRITE(6,202)
      WRITE(6,201)
C C C C C C C
*****
C*      CALCULATION OF SONIC VELOCITY AND AIR DENSITY BASE ON STANDARD
C*      ATMOSPHERE TABLE
C*      *****
C*      THETA = 1. - 6.8753 E-06 * H
C*      SVEL = 1116.89 * SQRT(THETA)
C*      HTH = CA/1000.
C*      RHO = 0.0023769 * (1. + HTH*(-.02875 + .000275 * HTH))
C C C C C C C
*****
C*      SELECTION OF PROPER AIRFOIL DATA FOR TYPE OF AIRFOIL CHOSEN
C*      *****
C*      IF(TYPE .EQ. 1)GO TO 1
C*      IF(TYPE .EQ. 2)GO TO 2
C*      IF(TYPE .EQ. 3)GO TO 3
C*      IF(TYPE .EQ. 4)GO TO 4
C*      IF(TYPE .EQ. 5)GO TO 5
C*      IF(TYPE .EQ. 6)GO TO 6
C*      IF(TYPE .EQ. 7)GO TO 7
C C C C C C C
      NACA 0015 AIRFOIL CHARACTERISTICS
C C C
1      MCR0 = C.64
      CLMAX = 1.28
      CLA = 5.73
      GO TO 8
C C C
      SC1095 AIRFOIL CHARACTERISTICS
C C C
2      MCR0 = C.73
      CLMAX = 1.18
      CLA = 5.73

```



```

C
C
C
GO TO 8
NACA 63 A 410.5 AIRFOIL CHARACTERISTICS
3
MCR0 = 0.72
CLMAX = 1.37
CLA = 6.25
GO TO 8
C
C
C
NACA 0012 AIRFOIL CHARACTERISTICS
4
MCR0 = 0.72
CLMAX = 1.25
CLA = 5.73
GO TO 8
C
C
C
NACA 0010 AIRFOIL CHARACTERISTICS
5
MCR0 = 0.74
CLMAX = 1.22
CLA = 5.8
GO TO 8
C
C
C
NACA 0011 AIRFOIL CHARACTERISTICS
6
MCR0 = 0.73
CLMAX = 1.2
CLA = 5.73
GO TO 8
C
C
C
AH1-J CCBRA AIRFOIL CHARACTERISTICS
7
MCR0 = 0.72
CLMAX = 1.4
CLA = 5.73
AMAX = CLMAX/CLA
WRITE(6,312)R,C,B,w,VT,FPA,N,DA,H,RHD,SVEL,TWIST,TYPE,CLMAX,AMAX,
8
>
PI = 3.14159
AD = PI * (F**2)
SD = (8 * C)/(PI * R)
VI = SQR(W/(2.*RHO*AD))
CT = w/(AD * RHO * (VT**2))
D = 2 * R
GE = -.1276*(H/D)**4+.708*(H/D)**3-1.4569*(H/D)**2+1.5432*(H/D)
>
IF (H/C .GT. 1.55) GE = 1.0
BTL = 1.0 - (SQR(2.*CT)/B)

```



```

C      WRITE(6,210)CT,VI,AD,SD,BTL,GE
C      IF (N - GE .2)N = (N - .30*N)
C      VMAX = SQRT(W/2./RHO/AD)* (4./ (FPA/AD)) *.333334
65      VMAXK = VMAX/1.68894
C      WRITE(6,236)VFK
C      VF = VFK * 1.68894
C      MU = VF/VT
C      *****
C      BASIC PCWER CALCULATIONS
C      *****
C      VL = VF**2/(2.*VI**2)
C      PIT = (1./BTL)*(GE)*SQRT(-VL+SQRT(VL**2+1.))*W*VI/550.
C      PO = (SD*RHC*CDG*AD*(VT**3))*(1.+4.25*MU**2)/400.
C      PP = (.5 * RHO * FPA * (VF**3))/550.
C      PT = PO + PIT + PP
C      *****
C      CALCULATING DYNAMIC PARAMETERS FOR CYCLIC AND COLLECTIVE ANGLES
C      *****
C      C1 = (BTL**2 + .5 * MU**2)
C      C2 = (BTL**2 - .5 * MU**2)
C      T1 = .5 * C1
C      T2 = (BTL**2)/3. + (MU**2 * BTL * .5)
C      T3 = (BTL**2/4.) * (BTL**2 + MU**2)
C      T4 = (MU/2.) * (BTL**2 + MU**2/4.)
C      A11 = ((BTL**2*MU*.5 - (MU**3/8.))*4.)/(BTL**2*C2)
C      A12 = (8.*ML*BTL)/(3.*C2)
C      A13 = (2.*ML*BTL**2)/C2
C      A14 = (BTL**2 + 1.5*MU**2)/C2
C      *****
C      CALCULATION OF INFLOW ANGLE LAMBDA
C      *****
C      IF (VF .GT. 0.0) GO TO 66
C      ALPHA = 0.0
C      WRITE(6,248)ALPHA
C      *****
66      LAMBDA1 = -SQRT(CT/2.)
C      IF (MU .LE. 0.1)GO TO 68
C      OP = PP * 550/VF
C      ALPHA = -OP/W
C      WRITE(6,247)DP,ALPHA
C      LAMBDA = -C1/SQRT(2*(LAMBDA1**2) + MU**2) + MU * TAN(ALPHA)
67      DLAMB = LAMBDA - LAMBDA1

```



```

LAMBDA1 = LAMBDA
LREF = ABS(CLAMB)
IF (LREF .GE. LERR) GO TO 67
LAMBDA = LAMBDA1
68
C** SOLVING SIMULTANEOUS EQUATIONS FOR CYCLIC AND COLLECTIVE ANGLES **
C** **
C31
E1 = (2.*CT)/(SD*CLA)
E2 = T1*LAMBDA
E3 = T3*TWIST
D1 = ((2.*CT)/(SD*CLA)) - T1*LAMBDA - TWIST*T3
D2 = -(A11*LAMBDA) - (TWIST*A13)
CYCLIC = ((C2*T2) - (D1*A12)) / (T2*A14 - T4*A12)
COLL = (D1 - T4*CYCLIC) / T2
THETA0 = COLL * 57.29578
THETA2 = CYCLIC * 57.29578
WRITE(6,209)A11,A12,A13,A14,T1,T2,T3,T4,LAMBDA
C** **
C** CALCULATION OF STALL DYNAMIC PARAMETERS & STALL CORRECTION FACTOR **
C** **
GAM = AMAX - COLL + CYCLIC
CS = MU * GAM + LAMBDA
BS = -MU * TWIST - GAM
RT = (BS**2 - 4.*TWIST*CS)
IF(RT)2C,19,19
XS = (-BS + SQRT(RT))/(2.*TWIST)
X0 = -XS - ES/TWIST
WRITE(6,215)GAM,CS,BS,XS,X0
IF (XS - 1.)17,20,20
IF (XS)2C,20,21
17
C** **
C** CALCULATION OF STALL POWER **
C** **
21
CPS = (SD / (24.*PI)) * ((1.-MU)**2) * (1.-XS) * SQRT(1.-XS**2)
IF (XS+X0)/2. .GE. 1.0)KS = 1.0
IF ((XS+X0)/2. .GT. 1.0)GO TO 24
C** **
C** CALCULATES INBOARD STALL CORRECTION IF (-BS/2TWIST < 1.0) **
C** **

```



```

C
24 KS = -(BS/(2.*TWIST)+XS)/(1.-XS)
CPS = KS*.CPS
GO TO 25
20 CPS = 0.0
KS = 0.0
25 PS = CPS*RH(*AD*(VT**3)/550.
WRITE(6,216)KS,CPS
C*****
C* ANGLE OF ATTACK CALCULATIONS
C*****
C A90 = CCLL + CYCLIC + TWIST + LAMBDA/(1.+MU)
A270 = CCLL - CYCLIC + TWIST + LAMBDA/(1.+MU)
A90D = A90 * 57.29278
A270D = A270 * 57.29278
WRITE(6,217)A90,A270
WRITE(6,223)CYCLIC,COLL,A90D,A270D
C*****
C* CALCULATION OF COMPRESSIBILITY POWER
C*****
26 MT = (VF+VT)/SVEL
MCRIT = MCRIC - CLA * A90 * .113
IF (MT - 1.0)28,27,27
27 WRITE(6,240)
GO TO 32
28 DM = MT-MCFIT - 0.06
IF (DM)32,32,30
30 CPC = SC*(0.012*DMD+.1*(DMD**3))
GO TO 33
32 CPC = 0.0
DM = 0.0
33 PM = CPC*RH(*AD*(VT**3)/550.
C*****
C* CALCULATION OF TOTAL POWER
C*****
PT1 = PT+PM+PS
WRITE(6,230)MT,MCRIT,DM,DMD,CPC,PT1,PO,PP,FM,PS,PT1
TSHP = 1.13*PT1 + 10.0
VFK = VF / 1.68894
VFK = VFK + DVFK
IF (VFK.LT.VMAX) GO TO 65
CENT = CENT + 1
IF (CENT.GT.100) GO TO 97
VFK = VMAX

```



```

229 > 5X, ALPHA(270) (DEG), STALL POWER CALCULATIONS, //, F10.6//
230 > 5X, 1CX, HIGH SPEED MACH EFFECTS, //, G12.6//
231 > 5X, ADVANCING BLADE TIP MACH NUMBER, //, G12.6//
232 > 5X, CRITICAL MACH NUMBER, //, G12.6//
233 > 5X, CRAG DIVERGENCE MACH NUMBER, //, G12.6//
234 > 5X, COMPRESSIBILITY POWER COEFF, //, G12.6//
235 > ***** POWER REQUIRED, //, *****
236 > ***** INDUCED POWER = , 6X, G12.6//, *****
237 > ***** PROFILE POWER = , 6X, G12.6//, *****
238 > ***** PARASITE POWER = , 5X, G12.6//, *****
239 > ***** COMPRESSIBILITY POWER = , G12.6//, *****
240 > ***** STALL POWER = , 9X, G12.6//, *****
241 > ***** TOTAL POWER REQUIRED = , G12.6//, *****
242 > 10X, FORWARD VELOCITY IN KNOTS = , G12.6//, *****
243 > ***** TIP MACH NUMBER GREATER THAN OR EQUAL TO 1.0, //, *****
244 > ***** ANGLE AT STALL ONSET = , 3X, G12.6//, *****
245 > 5X, STALL ONSET VELOCITY = , 3X, G12.6//, *****
246 > 5X, VELOCITY MAX ENDURANCE = , 3X, G12.6//, *****
247 > 5X, MAXIMUM FORWARD VELOCITY = , G12.6//, *****
248 > ***** DIFFERENCE BETWEEN A270 AND AMAX = , G12.6//, *****
249 > 5X, ACCEPTABLE ERROR = , G12.6//, *****
250 > ***** DISK PLANE ANGLE OF ATTACK = , F10.6//, *****
251 > ***** INITIAL STALL ONSET VELOCITY APPROXIMATION (KTS) = , *****
252 > ***** COEFFICIENT OF THRUST, *****
253 > ***** INDUCED VELOCITY, *****
254 > ***** DISC AREA, *****
255 > ***** SOLIDITY, *****
256 > ***** TIP-LOAD FACTOR, *****
257 > ***** GROUND EFFECT RATIO, *****
258 > ***** RADIUS, *****
259 > ***** MAIN ROTOR CHORD, *****
260 > ***** NUMBER OF MAIN ROTOR BLADES, *****
261 > ***** AIRCRAFT GROSS WEIGHT, *****
262 > ***** ROTOR TIP VELOCITY, *****
263 > ***** HORIZONTAL FLAT PLATE AREA, *****
264 > ***** NUMBER OF ENGINES IN HELICOPTER, *****
265 > ***** DENSITY ALTITUDE, *****

```



```

>      * MAIN ROTOR HEIGHT ABOVE GROUND... ',G12.6/,
>      * AIR DENSITY (RHO)..... ',F12.5/,
>      * SONIC VELOCITY..... ',G12.6/,
>      * BLADE GEOMETRIC TWIST..... ',G12.6//,
>      * TYPE AIRFOIL..... ',G12.6/,
>      * MAXIMUM 2-D LIFT COEFFICIENT..... ',G12.6/,
>      * 2-D STATIC STALL ANGLE (AMAX)..... ',G12.7/,
>      * LIFT CURVE SLOPE (/RAD)..... ',G12.6/,
>      * ZERO-LIFT DRAG COEFFICIENT..... ',F12.6/,
>      * CRITICAL MACH NO (FOR CL = 0)..... ',F12.5//
>      * INITIAL FORWARD VELOCITY (KT)..... ',G12.6/)

```

END

F. SAMPLE OF IBM COMPUTER OUTPUT

This section contains an example run of the IBM computer program, utilizing AH1-J Cobra data, starting at a forward velocity of 120 knots and terminating at VMAX.

HIGH SPEED FORWARD FLIGHT ANALYSIS

INPUT DATA

RADIUS.....	22.0000
MAIN ROTOR CHCRC.....	2.25000
NUMBER OF MAIN ROTOR BLADES.....	2.00000
AIRCRAFT GROSS WEIGHT.....	10612.0
ROTOR TIP VELOCITY.....	738.000
HORIZONTAL FLAT PLATE AREA.....	17.0000
NUMBER OF ENGINES IN HELICOPTER..	2.00000
DENSITY ALTITUDE.....	1000.00
MAIN ROTOR HEIGHT ABOVE GROUND...	1000.00
AIR DENSITY (RHO).....	0.002309
SONIC VELOCITY.....	1113.04
BLADE GEOMETRIC TWIST.....	-.174500
TYPE AIRFOIL.....	7.00000
MAXIMUM 2-D LIFT COEFFICIENT.....	1.40000
2-D STATIC STALL ANGLE (AMAX).....	.2443280
LIFT CURVE SLOPE (/RAD).....	5.73000
ZERO-LIFT DRAG COEFFICIENT.....	0.010750
CRITICAL MACH NC (FOR CL = 0)...	0.720000
INITIAL FORWARD VELOCITY (KT)....	120.000
COEFFICIENT OF THRUST.....	.554153E-02
INDUCED VELOCITY.....	38.8469
DISC AREA.....	1522.62
SOLIDITY.....	.650197E-01
TIP-LOSS FACTOR.....	.947362
GROUND EFFECT RATIO.....	1.00000

 FORWARD VELOCITY IN KNOTS = 120.000

PARASITE DRAG = 806.258
 DISK PLANE ANGLE OF ATTACK = -.759760E-01

DYNAMIC PARAMETERS

A11.....	0.625400
A12.....	0.806926
A13.....	0.573338
A14.....	1.175435
T1.....	0.467602
T2.....	0.319142
T3.....	0.218296
T4.....	0.125826
INFLOW RATIO (LAMBDA).....	-0.040381

STALL POWER CALCULATIONS

RT.....-0.106778E-01
 INBOARD STALL CORRECTION FACTOR.....0
 STALL POWER COEFFICIENT.....0

ANGLE OF ATTACK CALCULATIONS

LONGITUDINAL CYCLIC ANGLE.....-0.109613
 LONGITUDINAL COLLECTIVE ANGLE.....0.314954
 ALPHA(90) (DEG).....-0.048086
 ALPHA(270) (DEG).....12.511999

HIGH SPEED MACH EFFECTS

ADVANCING BLADE TIP MACH NUMBER...0.845135
 CRITICAL MACH NUMBER.....0.720543
 DRAG DIVERGENCE MACH NUMBER.....0.645919E-01
 COMPRESSIBILITY POWER COEFF.....0.521491E-04

POWER REQUIRED

INDUCED POWER = 151.545
 PROFILE POWER = 296.464
 PARASITE POWER = 297.103
 COMPRESSIBILITY POWER = 134.001
 STALL POWER = 0

TOTAL POWER REQUIRED = 879.112

FORWARD VELOCITY IN KNOTS = 130.000

PARASITE DRAG = 946.234
 DISK PLANE ANGLE OF ATTACK = -0.891604E-01

DYNAMIC PARAMETERS

A11.....0.680172
 A12.....0.880877
 A13.....0.625882
 A14.....1.207472
 T1.....0.470875
 T2.....0.325344
 T3.....0.221234
 T4.....0.126798
 INFLOW RATIO (LAMBDA).....-0.044668

STALL POWER CALCULATIONS

RT.....-.798416E-02

INBOARD STALL CORRECTION FACTOR..... .0

STALL POWER COEFFICIENT..... .0

ANGLE OF ATTACK CALCULATIONS

LONGITUDINAL CYCLIC ANGLE..... -0.122350

LONGITUDINAL COLLECTIVE ANGLE... 0.326189

ALPHA(90) (DEG)..... -0.291443

ALPHA(270) (DEG)..... 13.728103

HIGH SPEED MACH EFFECTS

ADVANCING BLADE TIP MACH NUMBER... .860309

CRITICAL MACH NUMBER..... .723294

DRAG DIVERGENCE MACH NUMBER..... .770157E-01

COMPRESSIBILITY POWER COEFF..... .630606E-04

POWER REQUIRED

INDUCED POWER = 139.900

PROFILE POWER = 308.957

PARASITE POWER = 377.740

COMPRESSIBILITY POWER = 162.039

STALL POWER = .0

TOTAL POWER REQUIRED = 988.636

FORWARD VELOCITY IN KNOTS = 140.000

PARASITE DRAG = 1097.41

DISK PLANE ANGLE OF ATTACK = -.103412

DYNAMIC PARAMETERS

A11..... 0.735630

A12..... 0.956563

A13..... 0.679659

A14..... 1.242629

T1..... 0.474411

T2..... 0.332042

T3..... 0.224407

T4..... 0.147888

INFLOW RATIO (LAMBDA)..... -0.050098

STALL POWER CALCULATIONS

RT.....-0.389701E-02

INBOARD STALL CORRECTION FACTOR.....0
STALL POWER COEFFICIENT.....0

ANGLE OF ATTACK CALCULATIONS

LONGITUDINAL CYCLIC ANGLE.....-0.136576
LONGITUDINAL COLLECTIVE ANGLE...0.339933
ALPHA(90) (DEG).....-0.520492
ALPHA(270) (DEG).....15.129103

HIGH SPEED MACH EFFECTS

ADVANCING BLADE TIP MACH NUMBER...0.875484
CRITICAL MACH NUMBER.....0.725882
DRAG DIVERGENCE MACH NUMBER.....0.896012E-01
COMPRESSIBILITY POWER COEFF.....0.745873E-04

POWER REQUIRED

INDUCED POWER = 129.913
PROFILE POWER = 322.449
PARASITE POWER = 471.789
COMPRESSIBILITY POWER = 191.657
STALL POWER = 0

TOTAL POWER REQUIRED = 1115.81

FORWARD VELOCITY IN KNOTS = 150.000

PARASITE DRAG = 1259.78
DISK PLANE ANGLE OF ATTACK = -0.118713

DYNAMIC PARAMETERS

A11.....0.791849
A12.....1.034170
A13.....0.734801
A14.....1.281051
T1.....0.478208
T2.....0.339237
T3.....0.227815
T4.....0.159103
INFLOW RATIO (LAMBDA).....-0.056720

STALL POWER CALCULATIONS

RT..... .230777E-02

VALUES FOR DETERMINING STALL COEFFICIENT

GAMMA = -C.26459390
CS = -C.14755023
BS = 0.32449627

XS = 0.7921403
XO = 1.0674362

INBOARD STALL CORRECTION FACTOR..... .662218094
STALL POWER COEFFICIENT..... .31202595E-04

ANGLE OF ATTACK CALCULATIONS

LONGITUDINAL CYCLIC ANGLE..... -0.152545
LONGITUDINAL COLLECTIVE ANGLE... 0.356377
ALPHA(90) (DEG)..... -0.738687
ALPHA(270) (DEG)..... 16.740753

HIGH SPEED MACH EFFECTS

ADVANCING BLADE TIP MACH NUMBER... .890658
CRITICAL MACH NUMBER..... .728348
DRAG DIVERGENCE MACH NUMBER..... .102309
COMPRESSIBILITY POWER COEFF..... .867883E-04

POWER REQUIRED

INDUCED POWER = 121.281
PROFILE POWER = 336.941
PARASITE POWER = 580.279
COMPRESSIBILITY POWER = 223.009
STALL POWER = 80.1774

TOTAL POWER REQUIRED = 1341.69

FORWARD VELOCITY IN KNOTS = 160.000

PARASITE DRAG = 1433.35
DISK PLANE ANGLE OF ATTACK = -.135068

DYNAMIC PARAMETERS

A11		0.848907
A12		1.113897
A13		0.791445
A14		1.322899
T1		0.482267
T2		0.346927
T3		0.231457
T4		0.170453
INFLOW RATIO (LAMBDA)		-0.064591

STALL POWER CALCULATIONS

RT..... .115852E-01

VALUES FOR DETERMINING STALL COEFFICIENT

GAMMA	=	-0.30194968
CS	=	-0.17515445
BS	=	0.36584556
XS	=	0.7398598
X0	=	1.3566751

INBOARD STALL CORRECTION FACTOR.....	1.0000000
STALL POWER COEFFICIENT.....	.60549210E-04

ANGLE OF ATTACK CALCULATIONS

LONGITUDINAL CYCLIC ANGLE.....	-0.170535
LONGITUDINAL COLLECTIVE ANGLE....	0.375743
ALPHA(90) (DEG).....	-0.949361
ALPHA(270) (DEG).....	18.591431

HIGH SPEED MACH EFFECTS

ADVANCING BLADE TIP MACH NUMBER....	.905832
CRITICAL MACH NUMBER.....	.730729
DRAG DIVERGENCE MACH NUMBER.....	.115103
COMPRESSIBILITY POWER COEFF.....	.997223E-04

POWER REQUIRED

INDUCED POWER =	113.722
PROFILE POWER =	352.433
PARASITE POWER =	704.243
COMPRESSIBILITY POWER =	250.243
STALL POWER =	155.580

TOTAL POWER REQUIRED = 1582.23


```
*****
FORWARD VELOCITY IN KNOTS = 163.359
*****
```

PARASITE DRAG = 1494.16
DISK PLANE ANGLE OF ATTACK = -.140799

DYNAMIC PARAMETERS

```
A11..... 0.868277
A12..... 1.141191
A13..... 0.810842
A14..... 1.337756
T1..... 0.483689
T2..... 0.349022
T3..... 0.232734
T4..... 0.174297
INFLOW RATIO (LAMBDA)..... -0.067526
```

STALL POWER CALCULATIONS

RT..... .155987E-01

VALUES FOR DETERMINING STALL COEFFICIENT

```
GAMMA = -0.31570089
CS = -0.18555188
BS = 0.38093823
```

```
XS = 0.7336488
XO = 1.4493771
```

```
INBOARD STALL CORRECTION FACTOR..... 1.00000000
STALL POWER COEFFICIENT..... .61108760E-04
```

ANGLE OF ATTACK CALCULATIONS

```
LONGITUDINAL CYCLIC ANGLE..... -0.177082
LONGITUDINAL COLLECTIVE ANGLE... 0.382947
ALPHA(90) (DEG)..... -1.019017
ALPHA(270) (DEG)..... 19.272018
```

HIGH SPEED MACH EFFECTS

```
ADVANCING BLADE TIP MACH NUMBER... .910929
CRITICAL MACH NUMBER..... .731516
DRAG DIVERGENCE MACH NUMBER..... .119412
COMPRESSIBILITY POWER COEFF..... .104241E-03
```

POWER REQUIRED

INDUCED POWER = 111.388
PROFILE POWER = 357.861
PARASITE POWER = 749.536
COMPRESSIBILITY POWER = 267.855
STALL POWER = 157.023

TOTAL POWER REQUIRED = 1643.66

INITIAL STALL ONSET VELOCITY APPROXIMATION (KTS) = 76.

DIFFERENCE BETWEEN A270 AND A MAX = .299871E-03
ACCEPTABLE ERROR = .100000E-02

ANGLE AT STALL ONSET= 13.9811
STALL ONSET VELOCITY = 131.913
VELOCITY MAX ENDURANCE = 76.0347
MAXIMUM FORWARD VELOCITY = 163.359

G. COMPARISON OF PROGRAM OUTPUT VS TEST DATA

This section compares the output of the HP41-CV and IBM 3033 computer programs to actual flight test data gathered at the Naval Weapons System Center.

POWER REQUIRED VS VELOCITY **FOR THE AH1-J USING THE HP 41-CV**

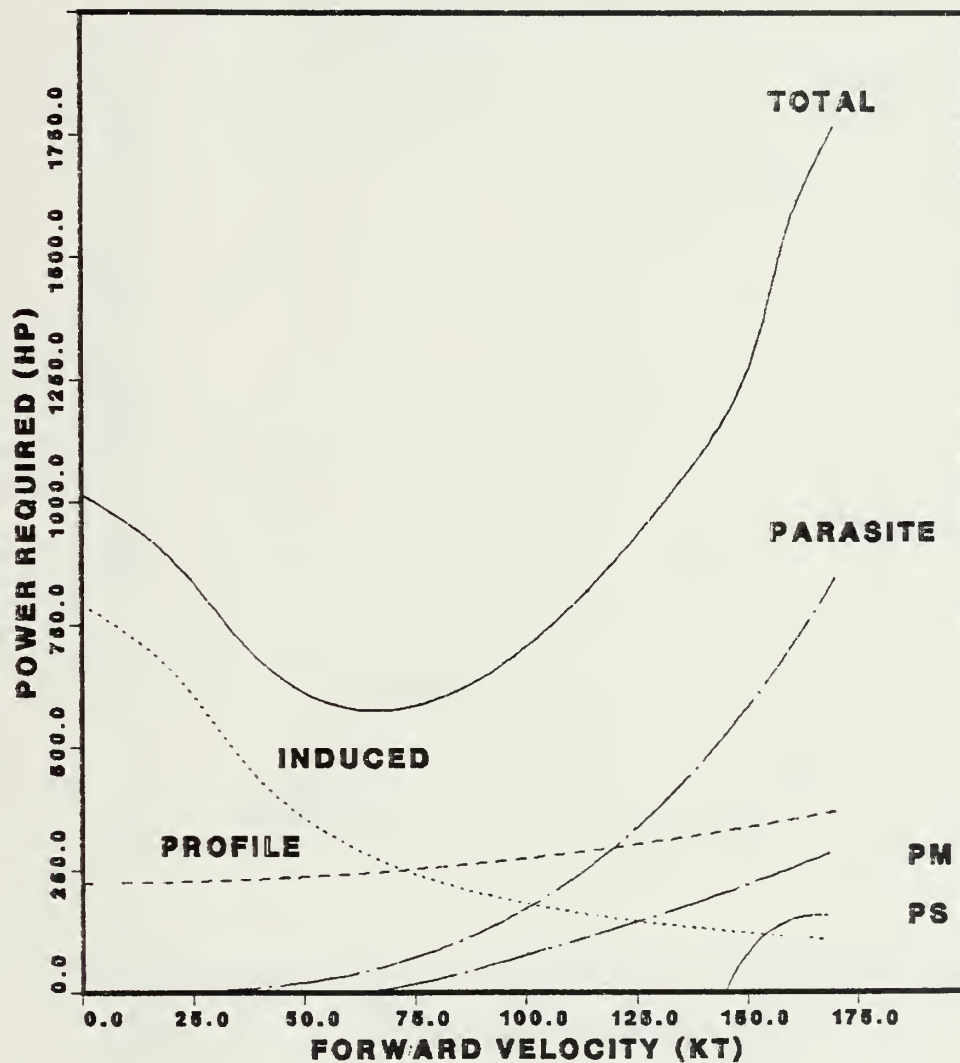


Figure C.1. Power Curves Generated by HP41-CV Program.

POWER REQUIRED VS VELOCITY FOR THE AH1-J USING THE IBM 3033

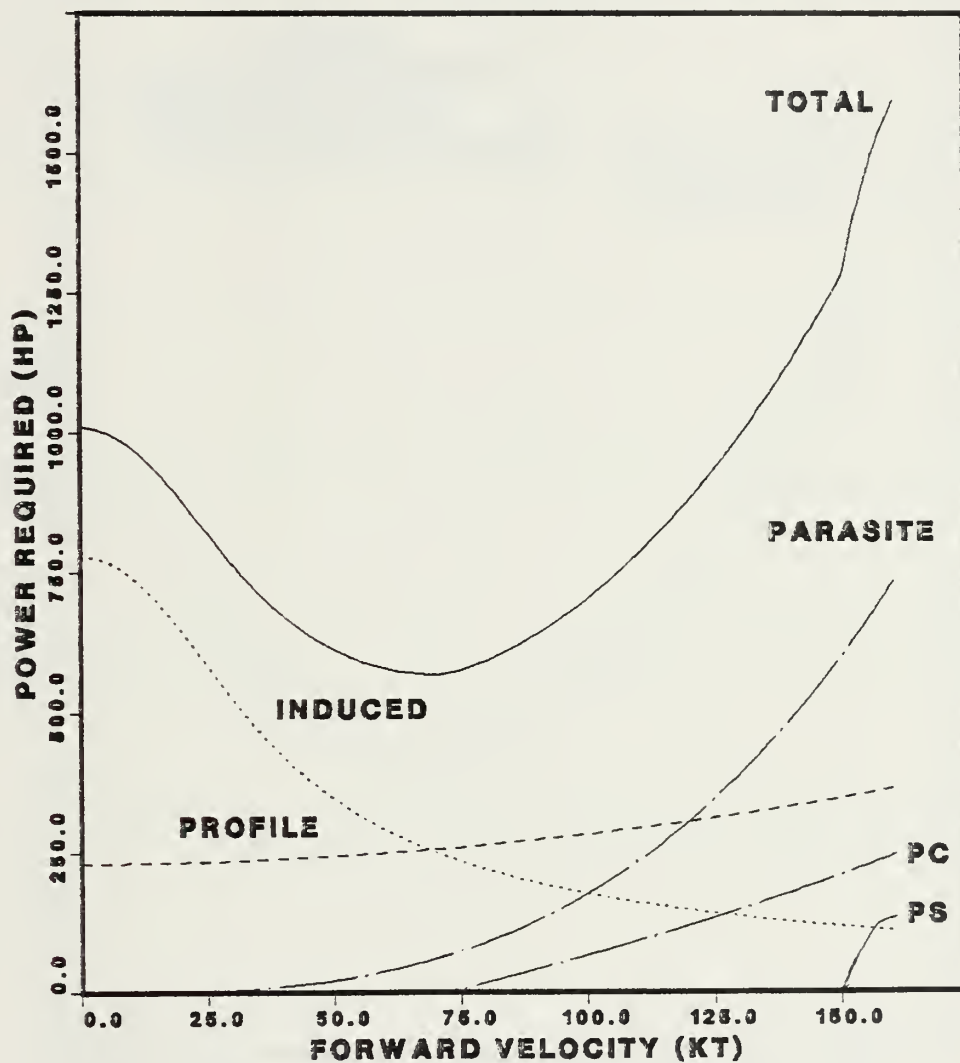


Figure C.2. Power Curves Generated by the IBM 3033 Program.

POWER REQUIRED VS VELOCITY

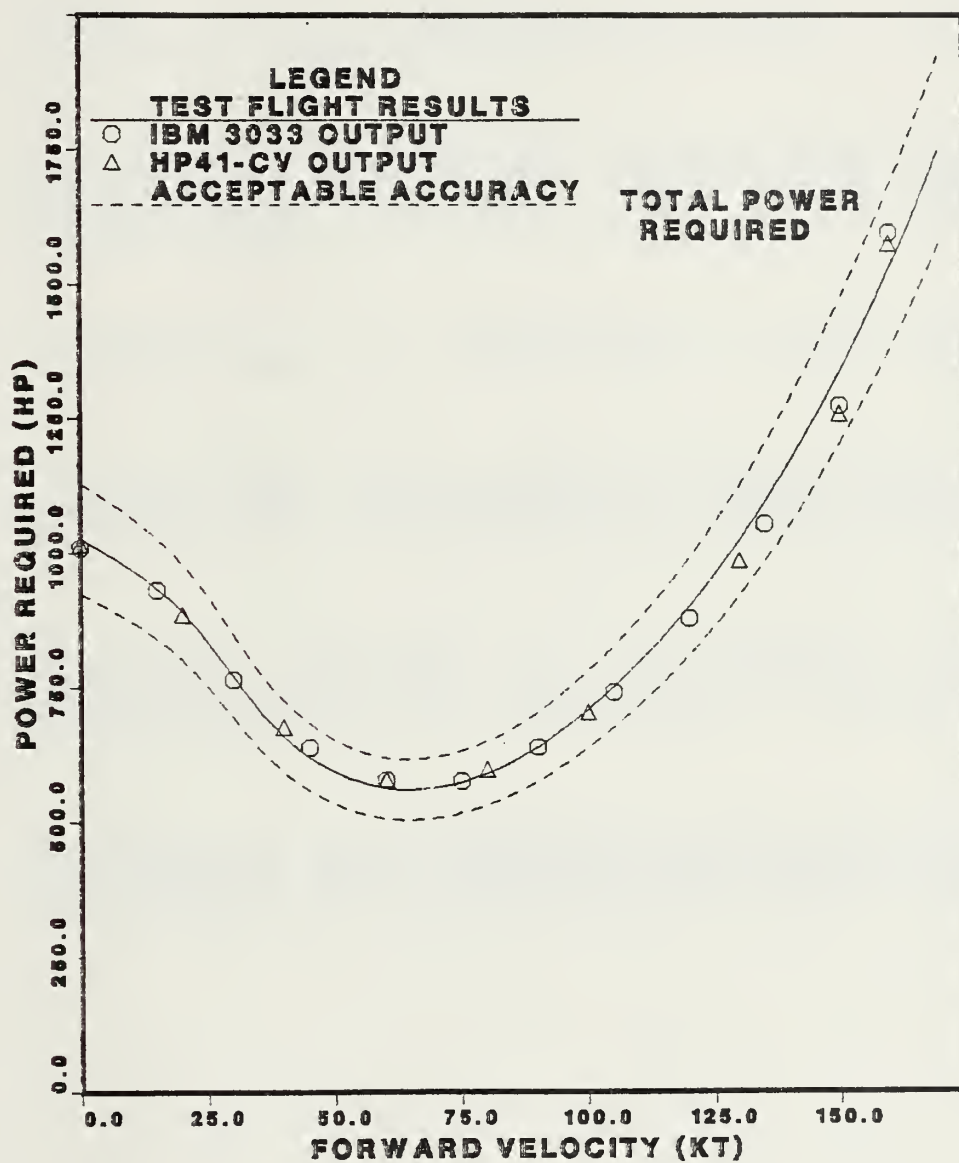


Figure C.3. Comparison Between Computer Data and Actual Test Flight Data.

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